Appendix A

FUTURE OZONE NONATTAINMENT PROJECTIONS

A. EPA Ozone NAAQS Analyses

In support of the revised ozone NAAQS, EPA projected future ambient ozone levels in 2010 to estimate the level of potential non-compliance with the revised standards. Baseline ozone air quality concentrations in 2010 were estimated using a Regional Oxidant Model (ROM) extrapolation methodology. Baseline in this context means that the only emission controls presumed were those already implemented or mandated by the CAA, with two exceptions. These two exceptions were that the projections also included the emission reductions from both the anticipated regional NOx emission control in the eastern U.S., which is discussed in the next section, and the National LEV program.

ROM air quality modeling information for 1990 and 2007 was used in combination with 1990 historical ozone air quality monitoring data to develop baseline 2007 ozone air quality for the 48 contiguous states. The 2007 predicted air quality was then adjusted to account for 2007/2010 emissions inventory differences and additional ozone modeling and monitoring information (1993 - 1995 Aerometric Information Retrieval System (AIRS) monitoring data, ROM and Urban Air Shed Modeling-V (UAM-V) air quality modeling data) to yield 2010 baseline ozone air quality data. Because this future air quality is based on counties with monitoring data in 1990, the centroid model was used to develop air quality for non-monitored counties through geographic interpolation. Initial nonattainment areas for alternative ozone standards were identified based on these modeled values for counties with ozone monitors in 1990. At the national level, nine areas were predicted to be in initial nonattainment of the current one-hour ozone standard; an additional 10 areas (19 total areas) were predicted to violate the 0.08 ppm NAAQS. These 19 areas encompassed a total of 203 counties with a total 1990 population of 78.6 million people.

B. OTAG SIP Call NPRM Analyses

EPA’s proposed OTAG SIP Call relied in part upon ozone modeling performed as part of the OTAG process. The OTAG process projected ozone levels in calendar year 2007. This year reflects the ozone NAAQS attainment deadline for a number of the severe ozone nonattainment areas within the OTAG region. OTAG performed baseline modeling which projected ozone levels in 2007 based on estimates of emissions which would occur in 2007 under established control programs. Included in the 2007 baseline are the net effects of growth and specific control programs prescribed by the 1990 Clean Air Act Amendments. The control measures included in the 2007 baseline are listed in Table A-1.

Table A-1. OTAG 2007 Baseline Control Measures

Emission Source Category	Control Programs
UTILITY	Title IV Controls (phase 1 & 2 for all boiler types) 250 Ton PSD and NSPS RACT & NSR in non-waived nonattainment areas (NAAs)
NON-UTILITY POINT/OTHER AREA	RACT at major sources in non-waivered NAAs 250 Ton PSD and NSPS CTG & Non-CTG RACT at major sources in NAAs & in Ozone Transport Region
OTHER AREA	Two Phases of Consumer & Commercial Products & One Phase of Architectural Coatings State 1 & 2 Petroleum Distribution Controls in NAAs Autobody, Degreasing & Dry Cleaning Controls in NAAs
NONROAD MOBILE	Federal Phase II Small Engine Standards Federal Marine Engine Standards Federal HDV (>= 50 hp) Standards - Phase I Federal RFG II (statutory and opt-in areas) 9.0 RVP maximum elsewhere in OTAG
HIGHWAY MOBILE	Tier 1 LDV and HDV Standards Federal RFG II (statutory and opt-in areas) High Enhanced I/M (serious and above areas) Low Enhanced I/M for rest of OTR Basic I/M (mandated areas) Clean Fuel Fleets (mandated areas) 9.0 RVP maximum elsewhere in OTAG On-board Vapor Recovery

Overall, OTAG estimated that domain wide emissions of NOx in the 2007 baseline are approximately 12 percent lower than 1990 while emissions of VOC are approximately 20 percent lower. The procedures for developing both 1990 and 2007 baseline inventories are described by Pechan.[1] The key findings from comparing the model predictions for the 2007 baseline to the 1990 base case scenario are:

- ozone levels are generally reduced across most of the region, including nonattainment areas;
- some increases in ozone are predicted in areas where higher economic growth is expected to occur, especially in the South;
- ozone levels aloft along regional "boundaries" are reduced, but average concentrations above 100 ppb and peak concentrations above 120 ppb are still predicted on several days; and

[1] *See* OTAG Emission Inventory Final Technical Report.

- ozone concentrations above the 1-hr and/or 8-hr NAAQS may still occur in the future under similar meteorological conditions in many of the counties currently violating either or both of these NAAQS.

The 2007 baseline emissions were reduced in an initial set of sensitivity modeling performed to assess several broad strategy-relevant issues. All of these model runs involved "across-the-board" emissions reductions (i.e., no source category-specific reductions). Based upon the findings of the sensitivity runs, OTAG subsequently developed and simulated source-specific region-wide control strategies in two rounds of modeling. These strategies were derived from a range of control measures applied to individual source categories of VOC and NOx. The controls were grouped into various levels of relative "stringency". The round-1 and round-2 modeling consisted of strategies that contained various combinations of controls from the least to most stringent for each source category.

The round-1 modeling was a "bounding analysis" with runs that ranged from the lowest level of control on all source categories (Run 1) to the highest level of control on all sources (Run 2). Runs 3 and 4b were included to isolate the effects of the most stringent OTAG controls on utilities only, versus this level of control on the other source categories. In the round-2 modeling, eight runs were simulated to examine the relative benefits of progressively increasing the level of control on utilities, under two alternative levels of control applied to area, nonroad and mobile sources.

The findings from the round-1 and round-2 OTAG strategy modeling that are particularly relevant are:

- Clean Air Act programs will likely provide a reduction in ozone concentrations in many nonattainment areas; however, some areas currently in nonattainment will likely remain nonattainment in the future and new 8-hr nonattainment and/or maintenance problem areas may develop as a result of economic growth in some areas;
- NOx reductions from elevated and low-level sources are both beneficial when considered on a regional basis; and,
- Further mitigation of the ozone problem will require regional NOx-oriented control strategies in addition to local VOC and/or NOx controls necessary for attainment in individual areas.

Because it models a regional control strategy for NOx similar to that proposed in the Ozone SIP Call NPRM and because control strategies for other sources are generally kept at Clean Air Act Amendment levels, Run 5 of the round-2 modeling is a principal focus for both the current OTAG analyses and the Tier 2 air quality assessment. The controls applied in Run 5 (shown in Table A-2) are believed to be the best current representation in the available modeling of the most likely scenario of control strategies to be in place in the time frame of potential Tier 2 emission standards.

Table A-2. OTAG Round 5 Control Strategies		
	Mandated CAA controls	Additional controls
UTILITY	* Acid Rain Controls (Phase 1 & 2 for all boiler types) * RACT & NSR in nonattainment areas (NAAs) without waivers	* OTC NOx MOU (Phase II) * 85 percent reduction from 1990 rate or rate-base of 0.15 lb/mbtu for all units, whichever is less stringent
NON-UTILITY POINT SOURCES	* RACT at major sources in NAAs without waivers * 250 Ton PSD and NSPS (not modeled) * NSR in NAAs without waivers (not modeled) * CTG & Non-CTG RACT at major sources in NAAs & throughout OTC * New Source LAER & Offsets for NAAs (not modeled) * "9 percent by 99" ROP Measures (VOC or NOx) for serious and above areas	* NOx Controls based on cost per ton of reduction (< $1,000 per ton) - primarily low NOx burner technology
NONROAD MOBILE	* Federal Phase II Small Engine Standards * Federal Marine Engine Standards * Federal HDV (>=50 hp) Standards-Phase 1 * Federal RFG II (statutory and opt-in areas) * 9.0 RVP maximum elsewhere in OTAG * "9 percent by 99" ROP Measures(VOC or NOx) for serious and above areas	* Federal Locomotive Standards (including rebuilds) * HD Engine 4 g/bhp-hr Standard
HIGHWAY MOBILE	* Tier 1 light-duty and heavy-duty Standards * Federal reformulated gas (RFG II) (statutory and opt-in areas) * High Enhanced I/M (serious and above areas) * Low Enhanced I/M for rest of OTR * Basic I/M (mandated areas) * Clean Fuel Fleets (mandated areas) * 9.0 RVP maximum elsewhere in OTAG * On board vapor recovery	* National LEV * Heavy Duty Vehicle 2 g/bhp-hr Standard * Federal Test Procedure (FTP) revisions * "9 percent by 99" ROP Measures (if substitute for VOC) in serious and above areas
OTHER AREA SOURCE CONTROLS	* Two Phases of Consumer & Commercial Products & One Phase of Architectural Coatings * Stage 1 & 2 Petroleum Distribution Controls-NAAs * Autobody, Degreasing & Dry Cleaning Controls in NAAs	None

In support of the proposed OTAG SIP Call, EPA developed procedures to project which counties would exceed the 1-hour and 8-hour ozone standards in 2007 based on 1993-1995 ambient ozone data and the benefits of future emission controls included in the OTAG strategy Run 5. This approach involved several steps that apply the ozone reductions predicted for Run 5 to ambient data to estimate the expected impacts of this strategy on ozone concentrations. In summary, the steps are:

(1) Calculate 1-hour and 8-hour ozone design values based on 1993-1995 monitoring data for each county;

(2) Use OTAG model predictions in a relative sense to estimate the change in 1-hour and 8-hour ozone levels expected as a result of the controls in Run 5;

(3) Apply the predicted percentage changes in 1-hour and 8-hour ozone to the 1993-1995 ambient design values to adjust these values to reflect the effects of the controls in Run 5; and

(4) Compare the adjusted design values to the level of the 1-hour or 8-hour NAAQS (i.e., 0.12 and 0.08 ppm) to estimate whether the Run 5 controls would provide for attainment.

This analysis projected that 12 counties in the OTAG area would be expected to remain in nonattainment with the ozone 1-hour standard after the Run 5 emission controls were applied described above. These nonattainment counties contribute, in whole or in part, to eight specific Consolidated Metropolitan Statistical Areas (CMSA) or Metropolitan Statistical Areas (MSA). For the purpose of this study, a list of metropolitan areas that contain counties projected to have an 1-hour ozone nonattainment problem was developed and is presented in Table A-3, along with the 1990 populations of the metropolitan areas. Clearly, while the Run 5 controls are projected provide significant air quality benefits, the areas remaining in nonattainment and the populations affected are significant.

Table A-3. Areas and Populations Projected to Exceed 1-Hour and 8-Hour Ozone NAAQS after Run 5 Controls (1990 Census Populations)		
Metropolitan Area	1-Hour	8-Hour
Atlanta, GA MSA	2,959,500	2,959,500
Baton Rouge, LA MSA	528,000	--- *
Charlotte-Gastonia-Rock Hill, NC-SC MSA	---	1,162,140
Chicago-Gary-Kenosha, IL-IN-WI CMSA	---	8,239,820
Cincinnati-Hamilton, OH-KY-IN CMSA	---	1,817,569
Dallas-Fort Worth, TX CMSA	---	4,037,282
Houston-Galveston-Brazoria, TX CMSA	3,731,029	3,731,029
Manitowoc County, WI (not assigned to a metropolitan area)	82,507	82,507
Memphis, TN-AR-MS MSA	---	1,007,306
Milwaukee-Racine, WI CMSA	1,607,183	1,607,183
Nashville, TN MSA	---	985,026
New Haven-Bridgeport-Stamford-Waterbury-Danbury, CT NECMA	1,631,864	1,631,864
New York-No. New Jersey-Long Island, NY-NJ-CT-PA CMSA	17,830,586	17,830,586
Philadelphia-Wilmington-Atlantic City, PA-NJ-DE-MD CMSA	5,893,019	5,893,019
Pittsburgh, PA MSA	---	2,394,811
St. Louis, MO-IL MSA	---	2,492,348
Washington-Baltimore, DC-MD-VA-WV CMSA	4,222,830	4,222,830
Total Population	38,486,518	60,094,820

* Not projected to be in nonattainment with the NAAQS

EPA also projected that 39 counties in the OTAG area would be expected to remain in nonattainment with the ozone 8-hour standard after the Run 5 emission controls were applied described above . These nonattainment counties contribute, in whole or in part, to specific Consolidated Metropolitan Statistical Areas or Metropolitan Statistical Areas. The resulting list of metropolitan areas that contain counties projected to have an 8-hour ozone nonattainment problem are presented in Table A-3, along with the population of the metropolitan area. As can be seen, there are significantly more projected ozone nonattainment areas in 2007 under the 8-hour ozone standard than under the 1-hour standard.

At least three caveats apply to these ozone projections. First, these projections are based on air quality data from 1993-95. The data from this period will not be the basis for nonattainment area designations for the 8-hour ozone standard. Those designations will be made in the 2000 time frame and will be based on the most recent air quality data available at that time (1997-1999). Therefore, while EPA expects that the vast majority of new counties will attain as a result of the SIP Call regional NOx control strategy, the number of new counties may be more or less than the number indicated above.

Second, the estimate of which counties will attain the 8-hour standard is based on the specific assumptions made by the OTAG Group in Run 5. Because the NOx controls proposed by EPA in the OTAG NPRM are similar but not identical to those contained in Run 5, the estimate may change when this rule is final and implemented. Therefore, the estimate of which areas will attain the standards through the final regional NOx strategy may be higher or lower than the number indicated above.

Third, the OTAG model only covers the eastern two-thirds of the nation. Specifically, Arizona and California are not covered. Phoenix and numerous areas in California were projected in the ozone NAAQS rule to exceed the 1-hour and 8-hour ozone standards in the future. While the SIP Call analysis can be considered an update of the ozone NAAQS rule analysis for the eastern portion of the nation, only the NAAQS rule addressed the western part of the U.S. Therefore, the NAAQS rule projections for the west need to be added to those of the SIP Call analysis in order to provide a complete projection of future ozone nonattainment in the U.S.

C. Future Particulate Matter Nonattainment Projections

EPA recently established new NAAQS for particulate matter (62 FR, July 18, 1997). EPA revised the existing NAAQS for inhalable PM (PM_{10}) and established new NAAQS for fine PM (PM2.5). The existing NAAQS for PM_{10} were a 24-hour average of 150 $\mu g/m^3$, with one exceedance allowed per year, and an annual average of 50 $\mu g/m^3$. The annual average standard was left unchanged, as was the numerical level of the 24-hour standard. However, compliance with the 24-hour standard was changed from allowing one exceedance per year to a 99th percentile level (i.e., a statistical analysis of daily PM_{10} levels must show that the 99th percentile is 150 $\mu g/m^3$ or less).

The new NAAQS for PM2.5 have a similar statistical form as the new NAAQS for PM_{10}. The differences are that the 24-hour standard is 50 $\mu g/m^3$ (98% confidence level), while the annual standard is 15 $\mu g/m^{3.}$

In support of these new NAAQS, EPA projected future ambient PM levels in 2010 to estimate the level of potential non-compliance with the new standards. Baseline 2010 emissions were projected from 1990 by application of sector-specific growth factors (1995 Bureau of Economic Analysis estimates) and Clean Air Act-mandated controls to 1990 base year emissions. Total 2010 emissions of VOC, NOx, SO_2 and secondary organic aerosols were estimated to decrease from 1990 levels; however, emissions of primary PM_{10} and $PM_{2.5}$ were estimated to increase. Future ambient PM levels were also estimated after implementation of a National PM Strategy. This strategy was developed to bring all projected PM nonattainment into compliance with the new NAAQS. For the purpose of the Tier 2 study, the most relevant projections are those prior to implementation of the National PM Strategy. The National PM Strategy has not yet been implemented, and PM emission reductions from the Tier 2 standards would reduce the need for further PM emission control as envisioned in the National PM strategy.

Baseline particulate matter air quality concentrations in 2010 were estimated using the Phase II Climatological Regional Dispersion Model (CRDM). Initial nonattainment counties (i.e., prior to application of the National PM Strategy controls) for each PM_{10} and $PM_{2.5}$ standard were estimated based on these modeled air quality predictions for counties with PM monitors during 1993 - 1995. At the national level, 45 counties were estimated to be in nonattainment of the current PM_{10} standards (50/150- 1 expected exceedance) in 2010, while only 11 counties were estimated to be in initial nonattainment of the revised PM_{10} standards (50/150- 99th percentile). Before applying the National PM Strategy, 102 counties were estimated to violate the selected $PM_{2.5}$ standard (15/65- 98th percentile) incremental to the current PM_{10} standard in 2010.

For the purpose of the Tier 2 study, EPA developed the following list of counties and to exceed the revised PM_{10} NAAQS. Metropolitan areas are shown when the definition of the current PM_{10} nonattainment area consists of the entire CMSA or MSA. Only the county is shown when the definition of the current PM_{10} nonattainment area only consists of a county.

Table A-4. Projected PM_{10} Nonattainment Areas in 2010 and their 1990 populations

State	N/A Area or County	1990 Population
Arizona	Maricopa Co.	2,122,101
California	Coachella Valley	
	Imperial Valley	
	Los Angeles South Coast Air Basin	12,443,900
	Mono Basin	
	Owens Valley	
	Sacramento Co.	
	San Bernardino Co.	
	San Joaquin Valley	
	Searles Valley	
Colorado	Prowers Co.	13,347
	Routt Co.	14,088
Connecticut	New Haven Co.	804,219
Idaho	Shoshone Co.	13,931
	Bonner Co.	26,622
Illinois	Randolph Co.	
Iowa	Cerro Gordo Co.	
	Scott Co.	150,973
Louisiana	Ouachita Par.	142,938
Montana	Flathead Co.	29,218

	Fergus Co.	12,083
	Gallatin Co.	50,463
	Madison Co.	5,989
	Lame Deer	10,505
	Park Co.	14,484
Nebraska	Cass Co.	21,318
Nevada	Washoe Co.	254,667
	Clark Co.	741,368
New Mexico	Bernalillo Co.	480,577
Oregon	Lake Co.	7,186
	Lane Co.	282,912
	Umatilla Co.	59,249
Pennsylvania	Philadelphia Co.	1,585,577
South Dakota	Pennington Co.	81,343
Tennesee	Davidson Co.	
Texas	Harris Co.	2,818,199
	Lubock Co.	
Utah	Utah Co.	263,590
Washington	Spokane Co.	361,333
	Walla Walla Co.	48,439
West Virginia	Hancock	
Wyoming	Sweetwater Co.	38,823
Total		22,899,442

D. Revisions to MOBILE5b

This section describes the four types of modifications which were made to MOBILE5b. A more detailed description of the modifications made to MOBILE5b can be found in a separate EPA report.[2]

1. In-use Emission Deterioration Rates

Vehicle emissions in-use tend to increase with vehicle age and mileage. This is referred to as emission deterioration and is often a significant factor in determining the in-use emissions performance of real-world vehicles.

[2] "Methodology for Modifying MOBILE5b in the Tier 2 Study", EPA Technical Report, April, 1998.

When MOBILE5 was developed, The latest model vehicles in-use were certified to the Tier 0 emission standards. The projections of in-use emission deterioration in MOBILE5 for these vehicles were based on the testing of in-use Tier 0 vehicles which hd not yet been through an inspection and maintenance (I/M) program. The rate of emission deterioration for Tier 1 vehicles and LEVs had to be projected from emission data on Tier 0 vehicles.

In the process of developing MOBILE6, EPA is reviewing in-use emission data from both later Tier 0 vehicles and Tier 1 vehicles. EPA believes that the in-use emission deterioration rates proposed for these vehicles (and LEVs) in MOBILE6 will be significantly lower than those in MOBILE5. However, the proposed MOBILE6 estimates were not available at the time of this analysis. In lieu of the MOBILE6 estimates, rates, basic emission rates (zero-mile emissions plus emission deterioration rates) from California's CALIMFAC model were substituted into MOBILE5. The CALIMFAC basic emission rates are much lower than those in MOBILE5 and are consistent directionally with the basic emission rates expected to be used in MOBILE6.

The basic emission rates from CALIMFAC without I/M are plotted versus mileage in Figures A-1 through A-3, along with those from MOBILE5.

Figure A-1. LDV NMHC Emissions: MOBILE5 vs. T2AT, No I/M

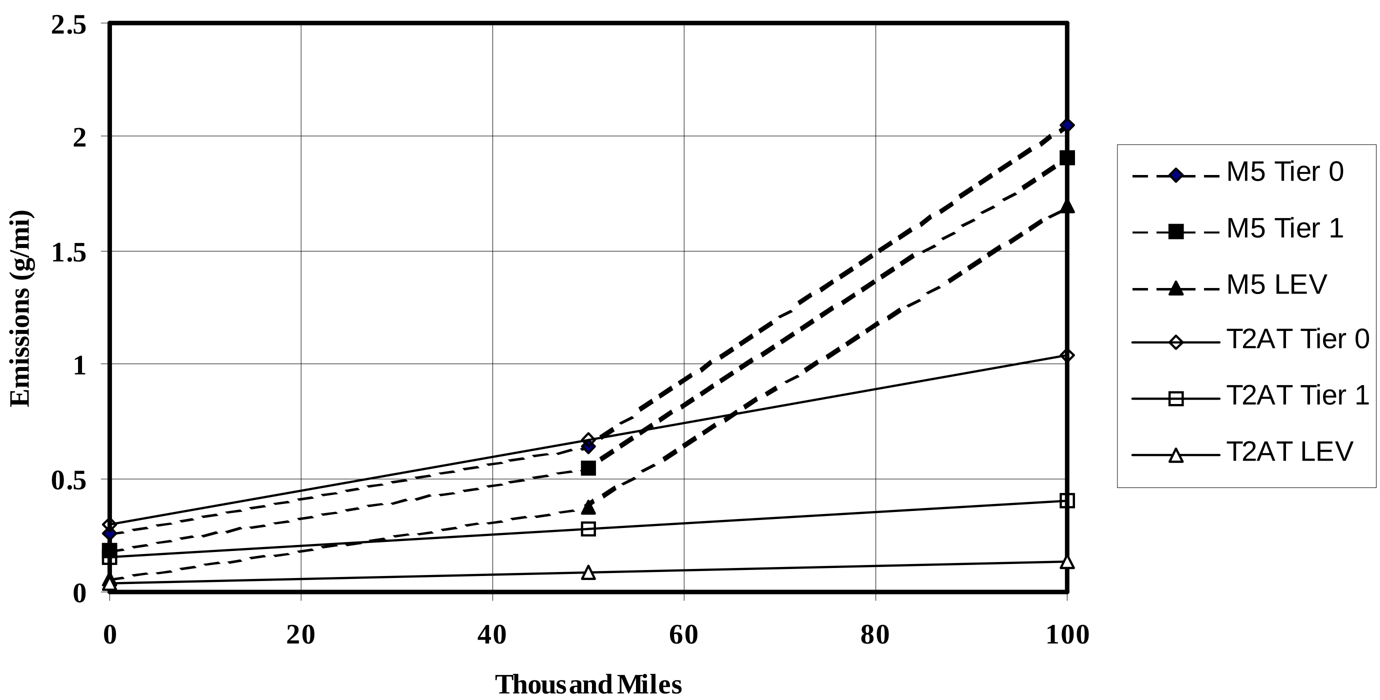
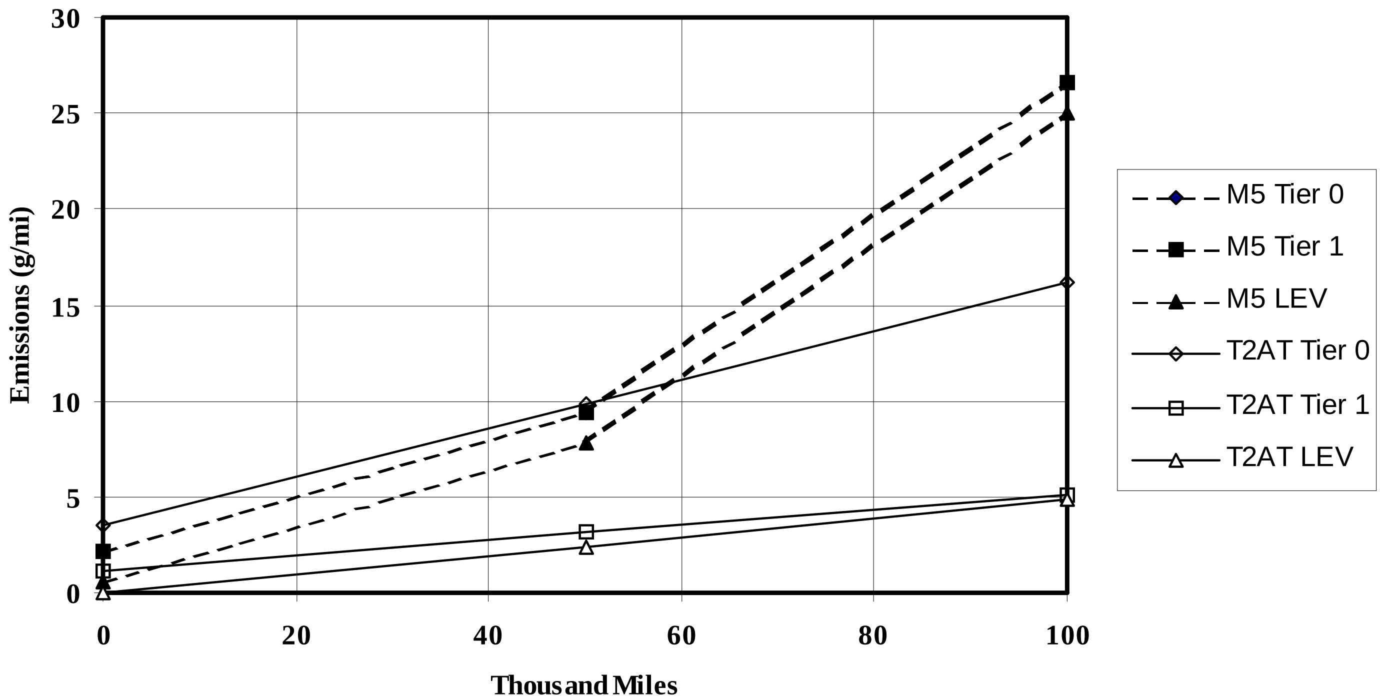
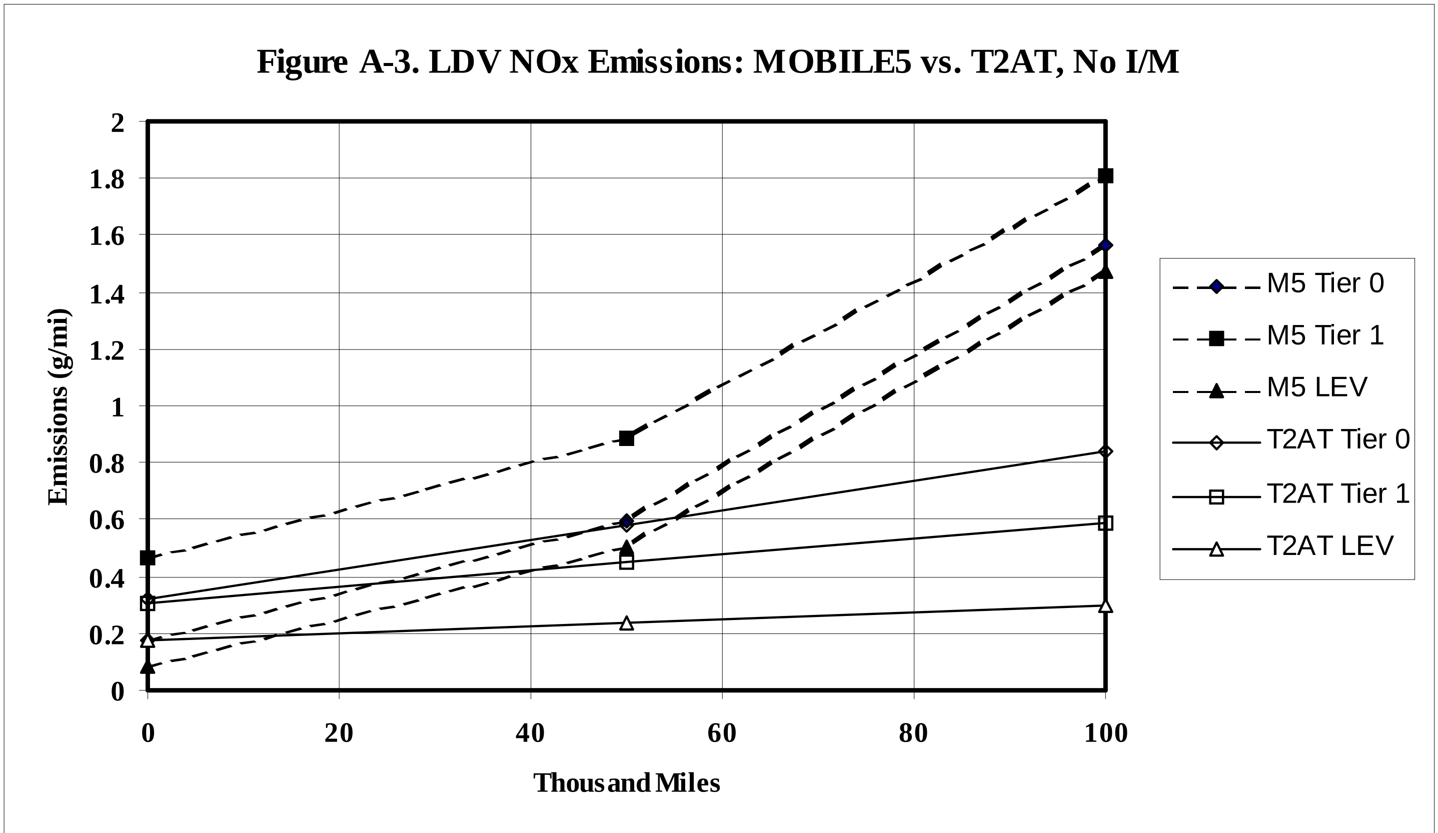


Figure A-2. LDV CO Emissions: MOBILE5 vs. T2AT, No I/M





As can be seen, the CALIMFAC rates for all three types of vehicles are much lower than those from MOBILE5. The emission factors with I/M are not shown. With I/M, however, the CALIMFAC emission factors for Tier 0 and 1 vehicles are still much lower than those from MOBILE5. With enhanced I/M, the CALIMFAC and MOBILE5 emission estimates for LEVs are much more similar.

2. Off-cycle Emission Effects and Their Control

"Off-cycle" emissions are those that occur during driving conditions not included in EPA's historical certification driving cycle, the LA-4 cycle. EPA promulgated emission standards for two specific off-cycle driving conditions in 1996, which will be effective starting with the 2000 model year. These two conditions are aggressive driving (high speeds and high accelerations) and driving with the air conditioner on. California implemented similar standards for vehicles meeting its LEV standards.

MOBILE5 does not include estimates of these off-cycle emissions, nor the effectiveness of off-cycle emission standards. MOBILE6 will contain such factors. However, as was the case for emission deterioration, the MOBILE6 off-cycle emission factors are not yet available. For this study, EPA developed estimates of these off-cycle emissions both before and after the implementation of off-cycle emission standards. These factors are based on EPA emission data obtained for the development of MOBILE6, as well as EPA and CARB analyses associated with their respective off-cycle emission rules. These off-cycle factors are in the form of multiplicative factors which are applied to the basic emission rates in MOBILE5b, which are based on emission measurements over the LA-4 cycle.

The off-cycle factors for a typical high ozone day are shown in Table A-5.

Table A-5. Off-Cycle Adjustment Factors			
	HC	**CO**	**NOx**
Prior to Off-Cycle Emission Control			
Tier 0 LDV/LDT1	1.24	2.24	1.70
Tier 0 LDT2/LDT3/LDT4	1.21	2.10	1.68
Tier 1 & LEV LDV/LDT1	1.78	2.90	1.75
Tier 1 & LEV LDT2/LDT3/LDT4	1.73	2.73	1.74
After Off-Cycle Emission Control			
Tier 1 LDV/LDT1	1.07	1.39	1.22
Tier 1 LDT2/LDT3/LDT4	1.08	1.46	1.20
LEV LDV/LDT1	1.03	1.46	1.11
LEV LDT2/LDT3/LDT4	1.04	1.48	1.10

As can be seen, the off-cycle emission factors for all types of vehicles prior to off-cycle emission control are quite substantial for all three pollutants. The implementation of off-cycle emission controls dramatically reduces the impact of these off-cycle conditions on in-use emissions. The EPA off-cycle standards eliminate roughly 70-90% of the off-cycle emission impact for Tier 1 vehicles. The CARB off-cycle standards eliminate roughly 80-95% of the off-cycle emission impact for LEVs.

3. Effect of Fuel Sulfur on Emissions

MOBILE5b indirectly includes two effects of fuel sulfur on LDV and LDT emissions. One, most testing of in-use vehicles utilizes Indolene as the test fuel. Indolene [3] differs in a number of ways from commercial gasoline. In particular, Indolene typically is very low in sulfur (40 ppm), versus average in-use conventional gasoline (not reformulated gasoline), which contains roughly 340 ppm. In developing in-use emission estimates for MOBILE5b, EPA adjusted Indolene-based emission measurements for these differences in fuel properties. Two, MOBILE5b includes the emission impacts of both Phase 1 and Phase 2 RFG.

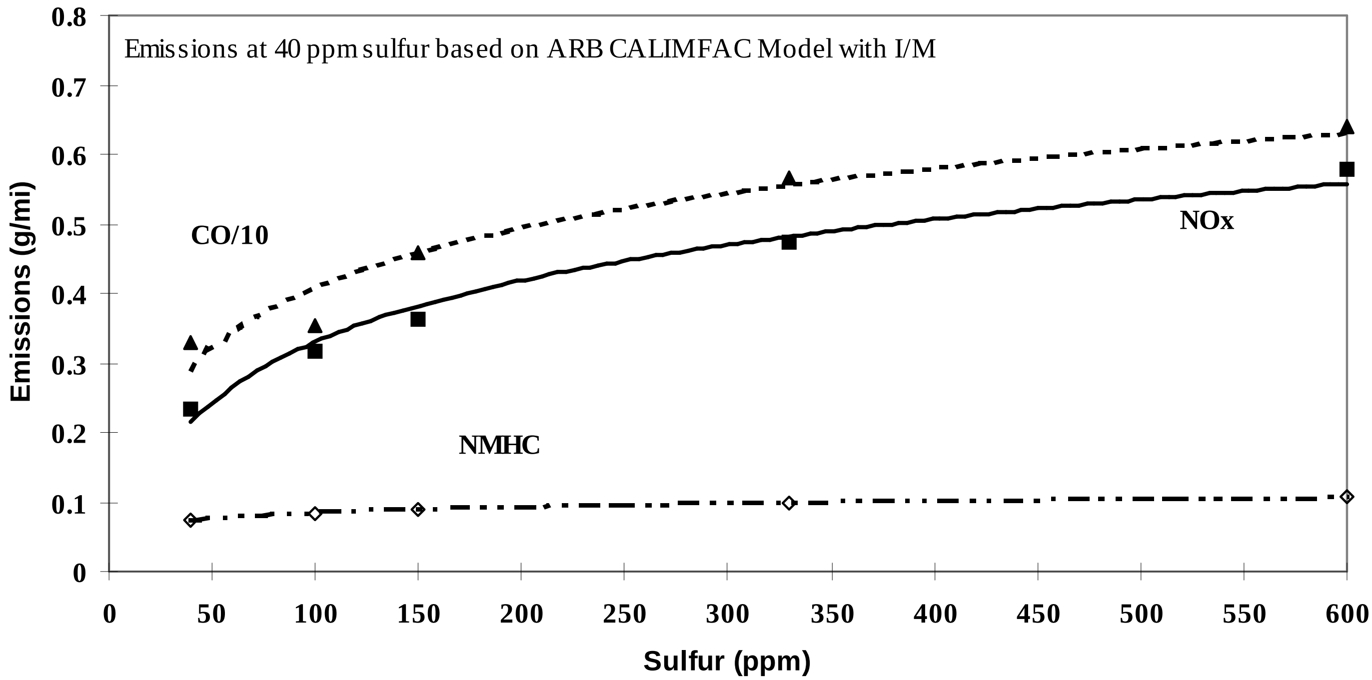
Both of these fuel adjustments are based on testing of Tier 0 vehicles. While the effects of fuel properties on Tier 1 vehicles do not appear to differ dramatically from Tier 0 vehicles, the effect of fuel sulfur content appears to have a much more dramatic effect on emissions from LEVs than either Tier 0 or Tier 1 vehicles. Thus, updated impacts of sulfur on emissions from

[3] Indolene is the official EPA certification fuel.

LEVs were developed for this study. These factors were based on the results of two recent test programs. One was conducted by the Coordinating Research Council (CRC) and involved 12 commercial California LEV LDVs and seven fuels. The other study was performed by members of the American Automobile Manufacturers Association (AAMA) and the Association of International Automobile Manufacturers (AIAM). This testing included 21 vehicles ranging from LDVs to LDTs, LEVs to ULEVs, and certified designs and designs which were deemed ready for certification. Three to five test fuels were used.

Figure A-4 presents these sulfur impacts graphically for LEV LDV/LDT1s. In this figure, the emissions at low sulfur levels (40 ppm) were taken from the CALIMFAC emission factors described above at representative in-use vehicle mileages and do not include off-cycle emissions.

Figure A-4: Effect of Sulfur on In-Use LEV Emissions



As can be seen, the impact of sulfur on LEV LDV and LDT1 emissions is significant for all three pollutants, but most so for NOx and CO. NMHC, CO and NOX emissions increase by 32%, 73%, and 102% between 40 and 350 ppm sulfur. While not shown in the figure, emissions from LEV LDT2s and LDT3s appear to be much less sensitive to sulfur than LEV LDV emissions.

4. Characterization of the LDT Fleet

Sales of LDTs have risen steadily over the past several years, significantly increasing market share and VMT relative to LDVs. As a result, the default VMT mix in MOBILE5 under-predicts the LDT share of both the in-use vehicle fleet and VMT. EPA is updating these factors in MOBILE6, but the updated estimates are not yet available. Therefore, an update of the contribution of LDTs to the in-use vehicle fleet and VMT was developed for the purpose of this study.

The basis for the updated LDT registration and mileage distributions, as well as the LDT fraction of LDV and LDT VMT, was a recently developed EPA model characterizing the growth in LDT sales and usage (hereafter referred to as the VMT model).[4] The LDT VMT fraction was further sub-divided between LDT1/LDT2s and LDT3/LDT4's using data from R.L. Polk.[5] As the VMT model also produced a revised registration distribution for LDVs, this was included in the modified MOBILEE5b model, as well.

The resultant VMT fractions for LDVs and LDTs are shown in Table A-6 below.

Table A-6. Light Duty VMT Fractions

Year	LDV		LDT1/2		LDT3/4	
	MOBILE5b	T2AT	MOBILE5b	T2AT	MOBILE5b	T2AT
2000	0.614	0.503	0.191	0.257	0.086	0.122
2005	0.600	0.450	0.197	0.293	0.087	0.139
2007	0.595	0.435	0.199	0.303	0.087	0.144
2010	0.589	0.415	0.201	0.317	0.088	0.150
2015	0.581	0.398	0.204	0.328	0.089	0.156
2020	0.575	0.391	0.207	0.333	0.089	0.158

As can be seen, the fraction of LDV VMT in the modified MOBILE5b model is much lower than was projected in MOBILE5b. (The emission factors from the modified MOBILE5b model are labeled “T2AT” in the chart, which is an acronym for Tier 2 Analysis Tool.) For example, by 2020, LDVs will represent less than 40% of combined LDV/LDT driving, while MOBILE5b projected nearly 60%. Most of the growth is in the LDT1 and LDT2 group, which includes small pick-ups, minivans and smaller sport utility vehicles. (MOBILE5b refers to this group as LDT1, while MOBILE5b refers to the LDT3/LDT4 group as LDT2. This is a carryover from the Tier 0 standards, where there were only two categories of LDTs.)

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[4] German, John., “VMT and Emission Implications of Growth in Light Truck Sales”, EPA Report.

[5] Accurex Environmental Corporation, “Update of Fleet Characterization Data for Use in MOBILE6", Report for EPA, May 1997.

Directionally, the changes in VMT mix and age distribution serve to increase overall emission inventory estimates relative to MOBILE5b. Since trucks have higher emission rates than vehicles and older trucks are dirtier than newer trucks, an increase in truck VMT and a flattened age distribution will increase the relative contribution of older trucks to overall inventory.

3. LDV/LDT Emissions in Urban Areas

The above modifications to MOBILE5b affect the projected emission factors of in-use light-duty vehicles. While the ultimate goal of this section is to project future motor vehicle emission inventories and ozone impacts, it is first useful to compare the gram per mile emission estimates from MOBILE5b with and without the above four modifications. Once these emission factors have been determined, they can be combined with local estimates of VMT for the various vehicle classes to develop local emission inventories. From there, airshed models can be used to assess ozone impacts.

To do this, EPA used MOBILE5b with and without the above mentioned modifications to estimate motor vehicle emission factors for three sets of local vehicle-related control strategies. These three control strategies generally represent the range of controls projected to be implemented in future ozone nonattainment areas in the OTAG and EPA regional ozone modeling described above. The three strategies are:

1) Federal Phase 2 RFG, National LEV program in 1997 and high enhanced I/M (applies to 2007 ozone nonattainment areas in the Northeast, such as New York City, Philadelphia, Washington, D.C. and Baltimore)

2) Federal Phase 2 RFG, National LEV program in 2001 and high enhanced I/M (applies to 2007 ozone nonattainment areas such as Houston, Chicago, Phoenix, Milwaukee, and Dallas)

3) Conventional gasoline, National LEV program in 2001 and high enhanced I/M (applies to 2007 ozone nonattainment areas, such as Atlanta, St. Louis, Charlotte, Nashville, Pittsburgh, and Cincinnati)

In addition to these three control scenarios, EPA evaluated a fourth scenario indicative of an area that is both in attainment with the ozone NAAQS and outside of any ozone transport region. Such an area would not have an I/M program, nor require RFG. However, they would be part of the National LEV program, as this program applies in all states outside of California which have not adopted the California LEV program.

MOBILE5b was run for calendar year 2007 for each of these four scenarios to approximate the emission factors which were used in the regional ozone modeling. Vehicle speed was assumed to be 24.7 miles per hour and the ambient temperature range was assumed to be 72-96 ^{o}F.

These emission factors only approximate those used in the regional ozone modeling. In the regional ozone modeling, separate MOBILE5 runs were made for each hour of a several day ozone transport period. Each run had different ambient temperatures and may have used varying vehicle speeds and VMT distributions across vehicle classes. Duplicating this methodology was beyond the scope of this study and, in any event, should not have affected the overall outcome of the comparison being made herein. The modifications to MOBILE5b described in the previous section apply at all vehicle speeds and ambient temperatures. Therefore, the relationship between the MOBILE5b and modified MOBILE5b exhaust emission factors should not be sensitive to the vehicle speed or ambient temperatures used in the model. The specific inputs used here were selected to be representative of average in-use vehicle speeds in urban areas and temperatures occurring on high ozone days.

Both MOBILE5b and the modified MOBILE5b were run for a range of calendar years (2000, 2005, 2007, 2010, 2015 and 2020) in order to indicate the change in emissions over time, as well as a direct comparison against MOBILE5b in 2007. Figures A-5 through A-7 present the NOx, NMHC, and CO emission factors for MOBILE5b with and without the modifications for the Northeast emission control scenario for all vehicles. The curves shown in the figures are simple least-square polynomial regressions. The MOBILE5b/Modified MOBILE5b comparison is very similar for the other two control scenarios which include high enhanced I/M.

Figure A-5. Fleet-wide NMHC Emissions
OTR NLEV with RFG and I/M

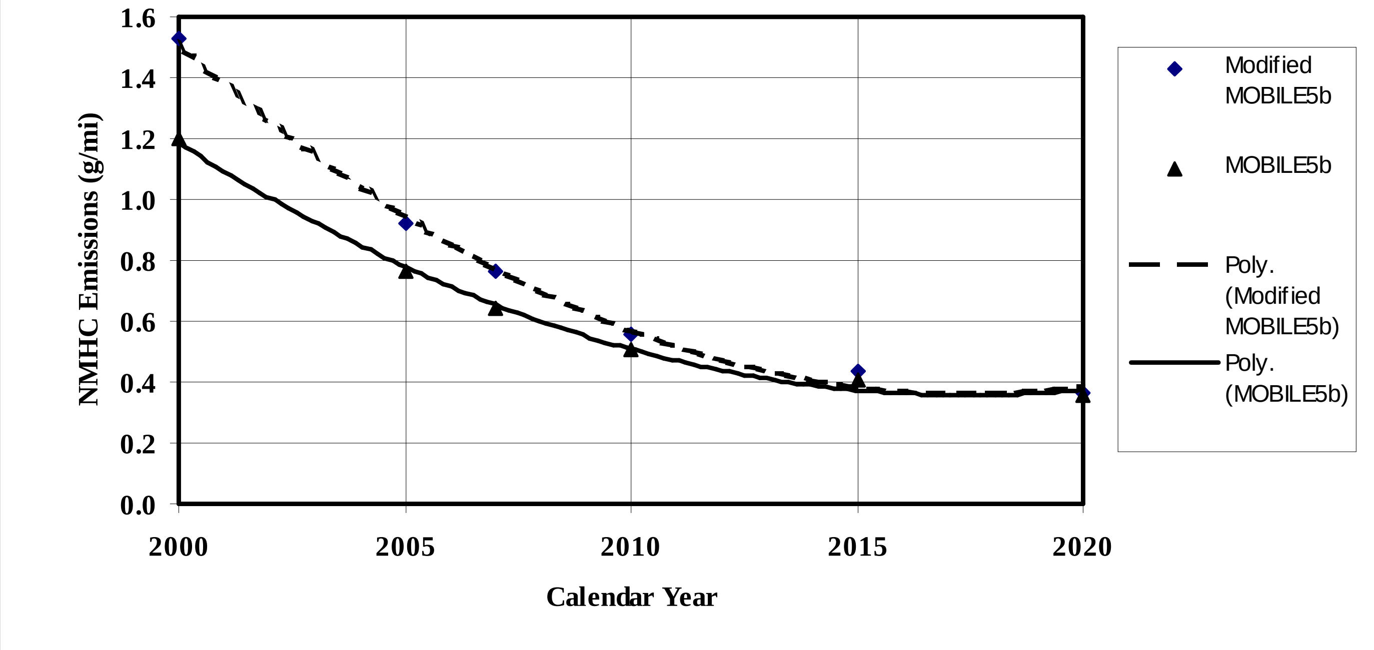
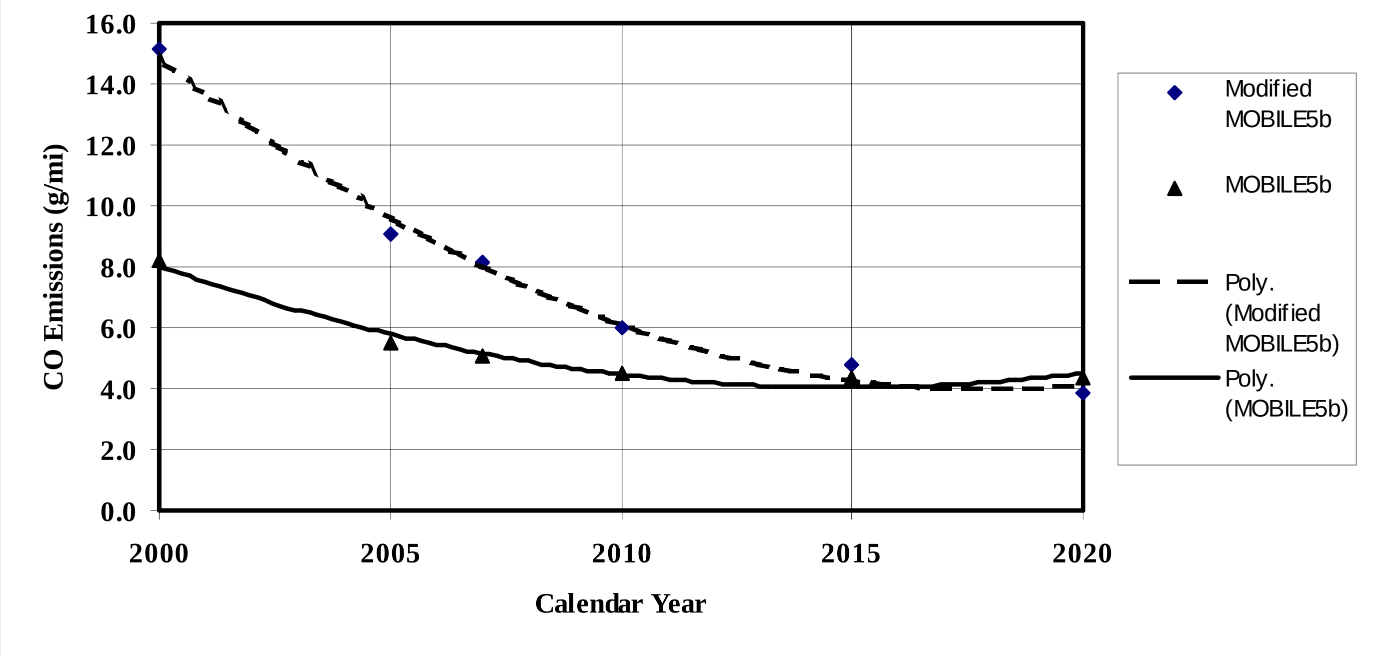
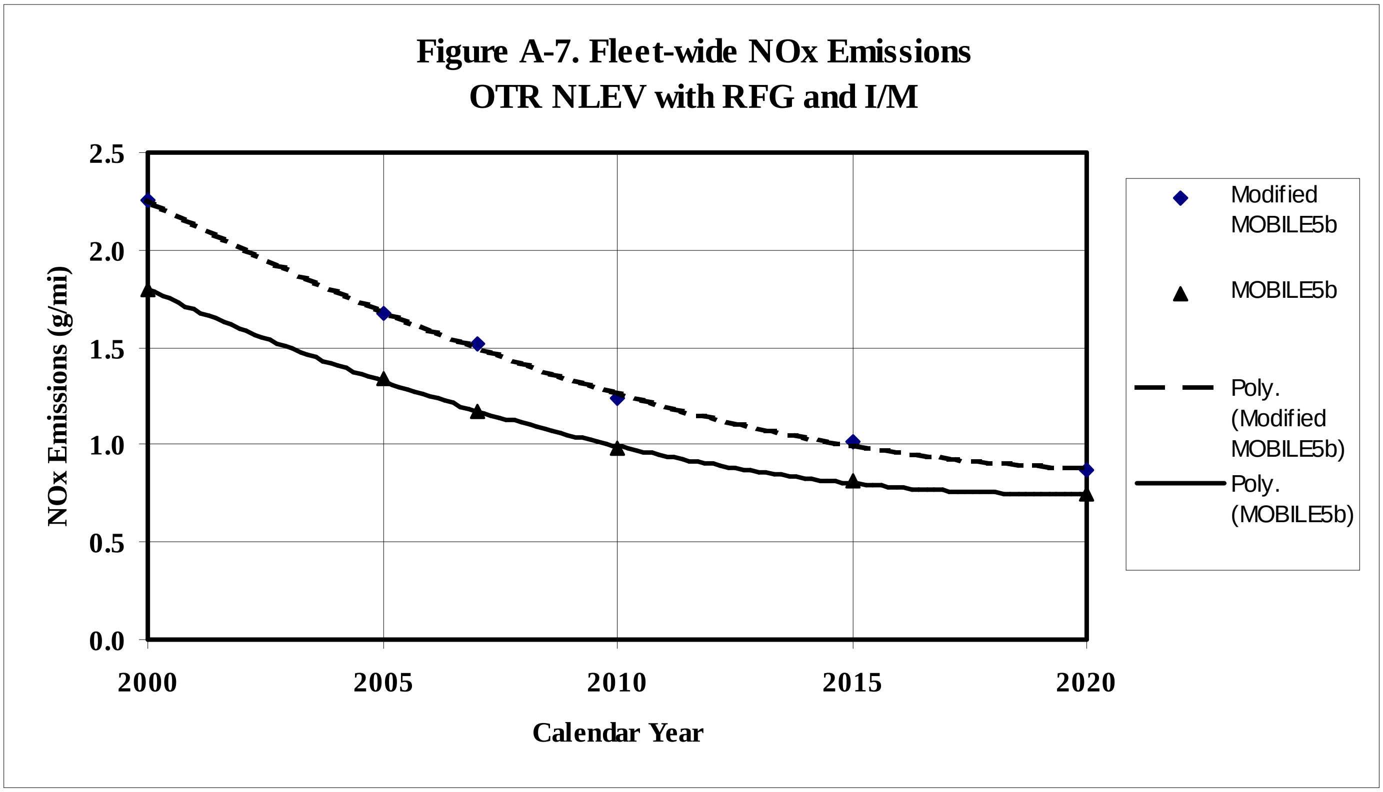


Figure A-6. Fleet-wide CO Emissions
OTR NLEV with RFG and I/M





As can be seen, the modified MOBILE5b model projects that NOx, NMHC, and CO emissions in 2007 will be roughly 18-15%, 61% and 30% higher, respectively, than as projected by MOBILE5b. This indicates that the effects of adding off-cycle emissions, an increased sulfur sensitivity for LEVs and updated LDT usage is greater than the effect of lower in-use deterioration rates.

Figures A-8 through A-10 present the emission factors for typical ozone attainment areas outside of ozone transport regions using both the modified and unmodified MOBILE5b models. In this case, the modified MOBILE5b model projects higher CO and NOx emission factors and lower NMHC emission factors in 2007 than MOBILE5b. NOx emissions with the modified MOBILE5b model fall below those of MOBILE5b after roughly 2008. The primary reason for the differences between this case and the Northeast ozone nonattainment case is the absence of high enhanced I/M in this case. The MOBILE5b projections for LEV emissions are very sensitive to the presence of high enhanced I/M. With high enhanced I/M, LEVs essentially meet their emission standards in-use. Without this degree of I/M, LEVs emit substantially above their standards.

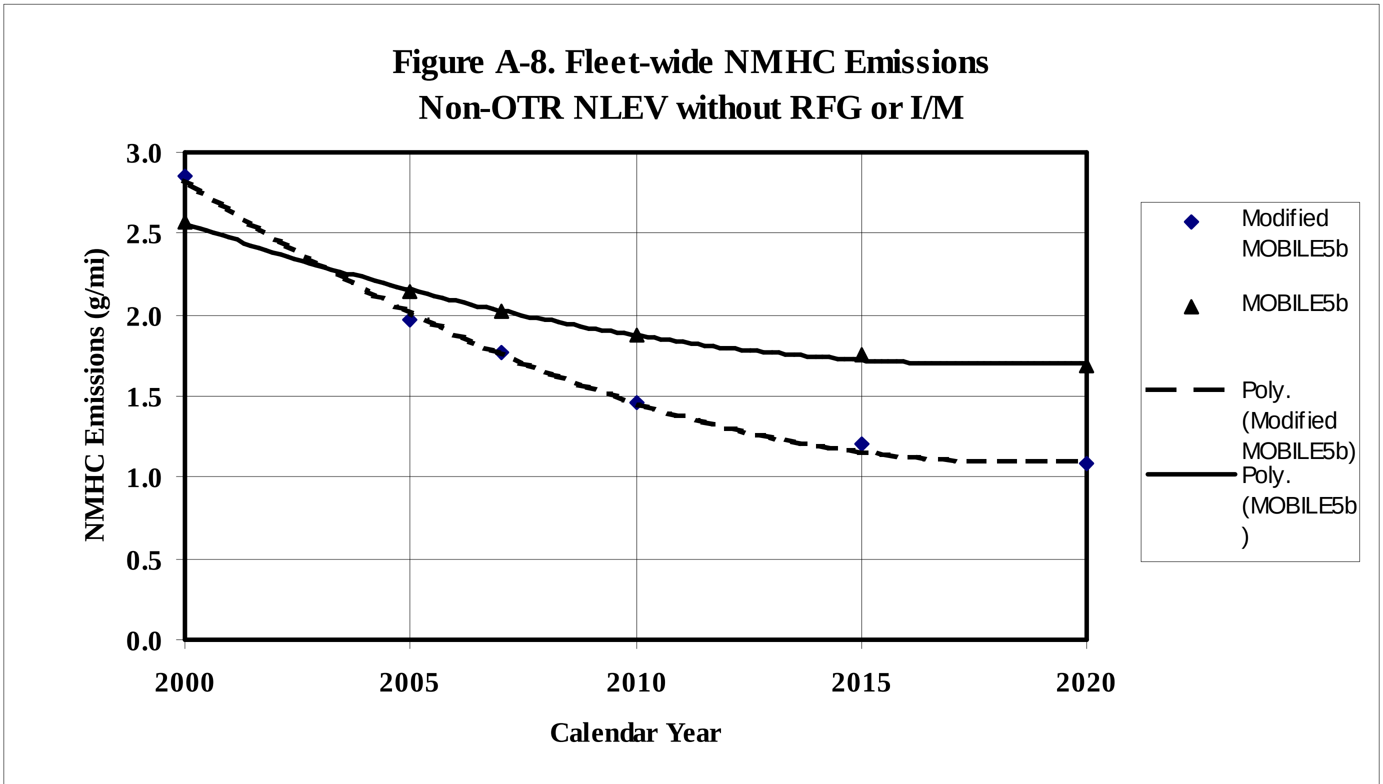


Figure A-8. Fleet-wide NMHC Emissions
Non-OTR NLEV without RFG or I/M
NMHC Emissions (g/mi)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
2000
2005
2010
2015
2020
Calendar Year
Modified MOBILE5b
MOBILE5b
Poly. (Modified MOBILE5b)
Poly. (MOBILE5b)

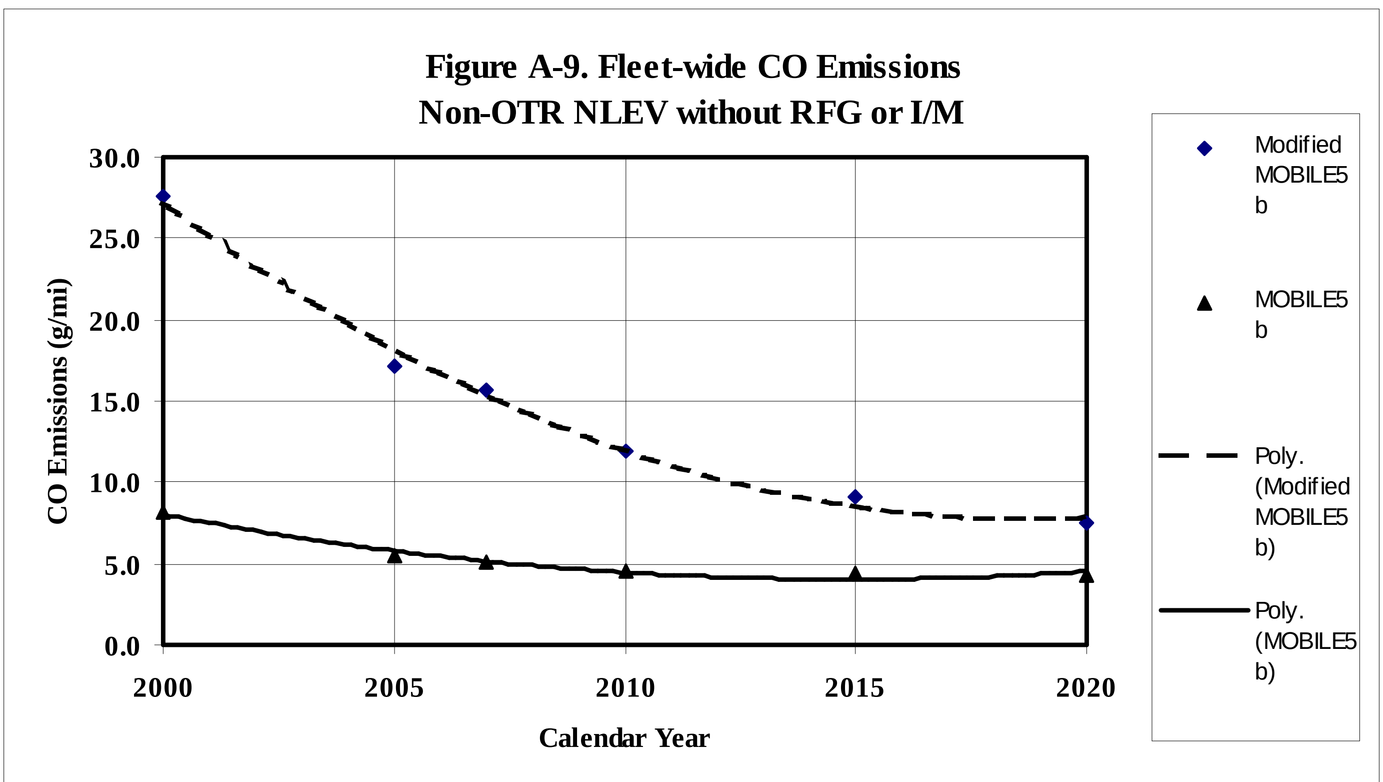
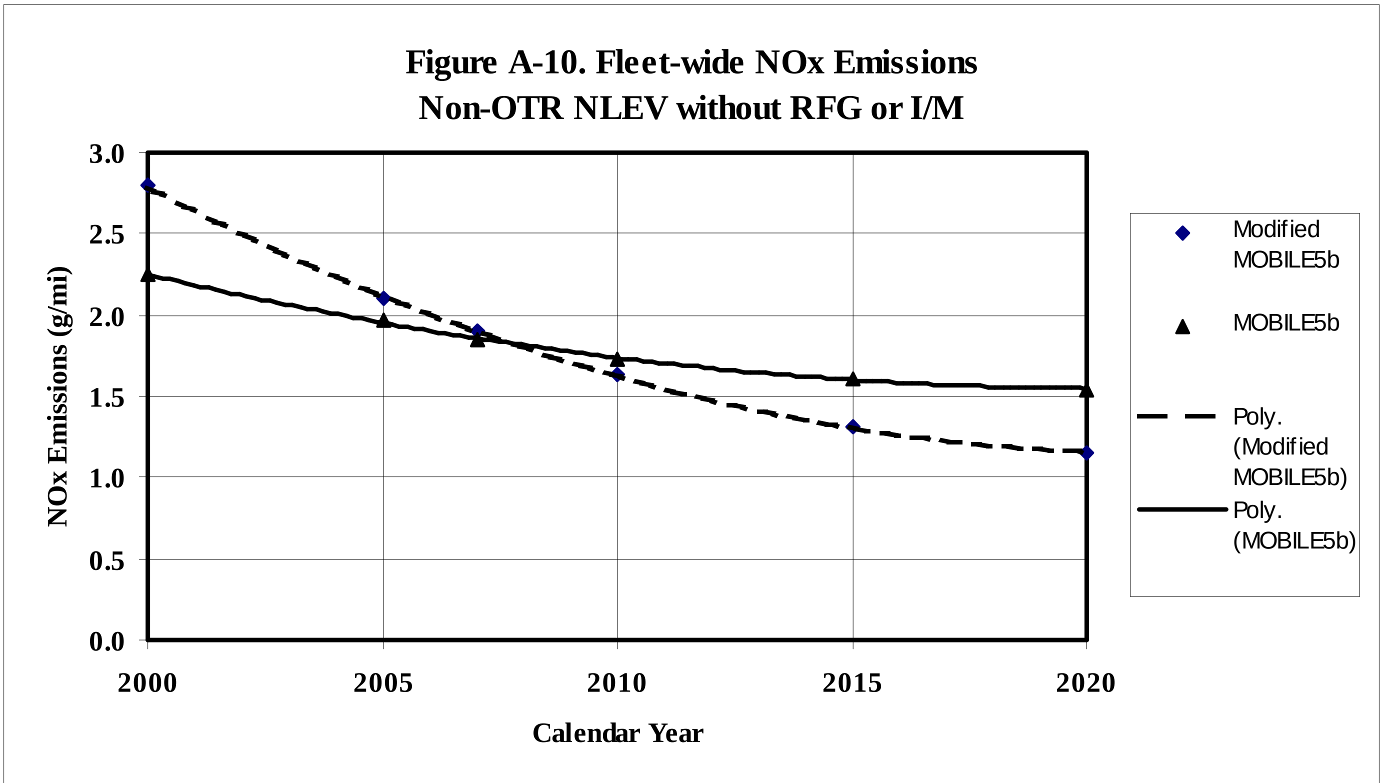


Figure A-9. Fleet-wide CO Emissions
Non-OTR NLEV without RFG or I/M
CO Emissions (g/mi)
30.0
25.0
20.0
15.0
10.0
5.0
0.0
2000
2005
2010
2015
2020
Calendar Year
Modified MOBILE5b
MOBILE5b
Poly. (Modified MOBILE5b)
Poly. (MOBILE5b)



With the lower in-use emission deterioration rates included in the modified MOBILE5b model, LEVs emit very close to their emission standards even without I/M. Therefore, there is very little difference in projected LEV emissions between the modified and unmodified MOBILE5b models when high enhanced I/M is present. In this case, the off-cycle, sulfur and truck-related effects dominate and emissions are higher with the modified model. However, without high enhanced I/M, the modified model projects much lower in-use emission deterioration rates for LEVs. These lower deterioration rates dominate the other factors and the modified model projects lower in-use emissions.

Thus, the modified MOBILE5b model projects higher emissions in ozone nonattainment areas which were projected to have high enhanced I/M in the OTAG modeling and sometimes lower, sometimes higher emissions elsewhere. One of the findings of OTAG was that a given amount of emissions occurring in or near the ozone nonattainment area had a greater ozone impact than emissions further upwind. The impact of upwind emissions was found to be significant, just not as significant as local emissions on a ton for ton basis. Given that emissions in the local ozone nonattainment areas are projected to be much higher with the modified model, the projected ozone levels in these areas are also likely to be higher, despite the possibility of lower emissions upwind.

An important factor in determining the impact of Tier 2 emission standards on ambient ozone is the relative contribution of LDV and LDT emissions in urban ozone nonattainment areas. The LDV/LDT inventory contribution will be estimated here for four such areas: New York City, Chicago, Atlanta, and Charlotte. The first three areas represent the three greatest ozone air quality challenges in the eastern U.S. according to the OTAG ozone modeling. Charlotte represents a smaller, but growing area with a growing ozone problem.

VOC and NOX emission inventories for high ozone days were developed as part of the OTAG modeling. Total emission inventories are available, as well as those for all on-road motor vehicles. However, separate emission inventories for light and heavy-duty vehicles were not made available. Because the VMT distributions by vehicle class used in the ozone modeling may have differed from the MOBILE5b default assumptions used in the previous section, separating the emissions from the two basic types of vehicles is not straightforward.

EPA estimated separate light and heavy-duty emissions in each of the four areas using a five step process.

1) A fleet-wide NOX emission factor applicable to the OTAG modeling of each specific area was determined by dividing the motor vehicle emission inventory by the total VMT used in developing the OTAG inventory.
2) The split between light and heavy-duty VMT was estimated by adjusting this ratio until the fleet-wide NOX emission factor from the unmodified MOBILE5b run described above matched that determined in step 1. In performing this match-up, the distribution of light-duty VMT between LDVs, LDT1s, and LDT2s was held constant, as was the distribution of heavy-duty VMT between gasoline and diesel vehicles.
3) Updated fleet-wide NMHC and NOX emission factors were estimated using the vehicle-class specific emission factors from the modified MOBILE5b runs and the VMT distributions determined in step 2.
4) Updated motor vehicle emission inventories were estimated by multiplying the OTAG inventories by the ratio of the fleet-wide emission factors determined in step 3 to the original OTAG emission factor estimated in step 1.
5) The LDV/LDT emission inventories were derived from the total motor vehicle inventories using the vehicle-class specific emission factors from the modified MOBILE5b model and the VMT distributions by vehicle class from step 2.

The results of this analysis for the four cities are shown in Tables A-7 through A-9. Emission inventories are shown for both light-duty and all motor vehicles. These are shown based on MOBILE5b both with and without modification. Also shown are total VOC, CO and NOX emission inventories from all sources. The non-motor vehicle emissions were taken directly from the OTAG Round 2 Run 5 emission inventories. As the non-motor vehicle CO emission inventories were not available from OTAG, these are not shown below.

Table A-7. VOC EMISSIONS - OTAG RUN 5 (tons/day)				
Metropolitan Area	Emission Model	Motor Vehicles		All Sources
		Light-Duty	Total	
Atlanta, GA MSA				
	MOBILE5b	65	92	389
	Modified MOBILE5b	81	109	406
Charlotte-Gastonia-Rock Hill, NC-SC MSA				
	MOBILE5b	33	58	235
	Modified MOBILE5b	42	67	243
Chicago-Gary-Kenosha, IL-IN-WI CMSA				
	MOBILE5b	107	146	908
	Modified MOBILE5b	137	176	938
New York-N. New Jersey-Long Island, NY--NJ-CT-PA CMSA				
	MOBILE5b	170	225	1,361
	Modified MOBILE5b	219	273	1,410

Table A-8. CO EMISSIONS - OTAG RUN 5 (tons/day)				
Metropolitan Area	Emission Model	Motor Vehicles		All Sources
		Light-Duty	Total	
Atlanta, GA MSA				
	MOBILE5b	591	815	-
	Modified MOBILE5b	1,160	1,384	-
Charlotte-Gastonia-Rock Hill, NC-SC MSA				
	MOBILE5b	204	340	-
	Modified MOBILE5b	399	535	-
Chicago-Gary-Kenosha, IL-IN-WI CMSA				
	MOBILE5b	946	1,220	-
	Modified MOBILE5b	1,781	2,054	-
New York-N. New Jersey-Long Island, NY--NJ-CT-PA CMSA				
	MOBILE5b	1,742	2,164	-
	Modified MOBILE5b	3,238	3,660	-

Table A-9. NOX EMISSIONS - OTAG RUN 5 (tons/day)				
Metropolitan Area	Emission Model	Motor Vehicles		All Sources
		Light-Duty	Total	
Atlanta, GA MSA				
	MOBILE5b	78	165	394
	Modified MOBILE5b	131	218	447
Charlotte-Gastonia-Rock Hill, NC-SC MSA				
	MOBILE5b	27	81	185
	Modified MOBILE5b	45	100	203
Chicago-Gary-Kenosha, IL-IN-WI CMSA				
	MOBILE5b	144	263	877
	Modified MOBILE5b	243	362	977
New York-N. New Jersey-Long Island, NY--NJ-CT-PA CMSA				
	MOBILE5b	257	437	1,204
	Modified MOBILE5b	430	611	1,377

The next two tables show the light-duty motor vehicle contribution to total emissions and the total motor vehicle contribution to total emissions for VOC and NOX.

Table A-10. VOC EMISSIONS - CONTRIBUTION TO TOTAL EMISSIONS (%)			
Metropolitan Area	Emission Model	Motor Vehicles	
		Light-Duty	All
Atlanta, GA MSA			
	MOBILE5b	17%	24%
	Modified MOBILE5b	20%	27%
Charlotte-Gastonia-Rock Hill, NC-SC MSA			
	MOBILE5b	14%	25%
	Modified MOBILE5b	17%	27%
Chicago-Gary-Kenosha, IL-IN-WI CMSA			
	MOBILE5b	12%	16%
	Modified MOBILE5b	15%	19%
New York-N. New Jersey-Long Island, NY--NJ-CT-PA CMSA			
	MOBILE5b	12%	17%
	Modified MOBILE5b	16%	19%

Table A-11. NOX EMISSIONS - CONTRIBUTION TO TOTAL EMISSIONS (%)			
Metropolitan Area	Emission Model	Motor Vehicles	
		Light-Duty	All
Atlanta, GA MSA			
	MOBILE5b	20%	42%
	Modified MOBILE5b	29%	49%
Charlotte-Gastonia-Rock Hill, NC-SC MSA			
	MOBILE5b	15%	44%
	Modified MOBILE5b	22%	49%
Chicago-Gary-Kenosha, IL-IN-WI CMSA			
	MOBILE5b	16%	30%
	Modified MOBILE5b	24%	37%
New York-N. New Jersey-Long Island, NY--NJ-CT-PA CMSA			
	MOBILE5b	21%	36%
	Modified MOBILE5b	31%	44%

As can be seen, based on MOBILE5b, the light-duty contribution to total emissions ranges from 12-17% for VOC and 15-21% for NOX. The light-duty contribution to total emissions increases to 15-20% for VOC and 22-31% for NOX based on the modified MOBILE5b model. The contribution of all motor vehicles is roughly 4-11% higher for VOC and 14-29% higher for NOX. The contribution of LDVs and LDTs to these emission inventories is substantial and merits further control, to the degree that it is cost effective.

Appendix B

VEHICLE TECHNOLOGY

The purpose of this appendix is to further expand upon the technical discussion that was presented in *Chapter IV. Assessment of Technical Feasibility*. For the purpose of continuity, some of same text from Chapter IV is included in this appendix.

Vehicle exhaust emissions can be reduced by a number of technologies, but the most potential for improvement exists in reductions to base engine-out emissions, improvement in air-fuel ratio control, better fuel delivery and atomization, and continued advances in exhaust aftertreatment.

The following descriptions provide an overview of the latest technologies capable of reducing exhaust emissions. The descriptions will also discuss the state of development and current production usage of the various technologies. It is important to point out that the use of all of the following technologies is not required to further reduce emissions. The choices and combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of existing emission control systems, and individual manufacturer preferences. As noted above, with the exception of a few technologies, many of these technologies are used in some Tier 1, TLEV, LEV and ULEV vehicles already in production.

In order to have a more complete understanding of the latest technologies, including the state of development and current production usage of the various technologies, EPA contracted Energy and Environmental Analysis, Inc. (EEA), to conduct a study evaluating the potential availability of emission control technology to meet more stringent emission standards for light-duty vehicles and light-duty trucks. The report is titled "Benefits and Cost of Potential Tier 2 Emission Reduction Technologies." EPA also used as references, the staff report on "Low-Emission Vehicle and Zero-Emission Vehicle Program Review," published in November 1996 by the State of California Air Resources Board (CARB), and information from the Manufacturers of Emission Controls Association (MECA) and numerous vehicle manufacturers.

A. Base Engine Improvements

There are several design techniques that can be used for reducing engine-out emissions, especially for HC and NOx. The main causes of excessive engine-out emissions are unburned HCs and high combustion temperatures for NOx. Methods for reducing engine-out HC emissions include the reduction of crevice volumes in the combustion chamber, reducing the combustion of lubricating oil in the combustion chamber and developing leak-free exhaust systems. Leak-free exhaust systems are listed under base engine improvements because any modifications or changes made to the exhaust manifold can directly affect the design of the base engine. Base engine control strategies for reducing NOx include the use of "fast burn" combustion chamber designs, multiple valves with variable-valve timing, and exhaust gas recirculation.

1. Combustion Chamber Design

Unburned fuel can be trapped momentarily in crevice volumes (the space between the piston and cylinder wall) before being subsequently released. Since trapped and re-released fuel can increase engine-out HC, the reduction of crevice volumes is beneficial to emission performance. One way to reduce crevice volumes is to design pistons with reduced top "land heights" (distance between the top of the piston and the first piston ring). The reduction of crevice volume is especially preferable for vehicles with larger displacement engines, since they typically produce greater levels of engine-out HC than smaller displacement engines. EEA estimates the emission reduction of reducing crevice volumes in the combustion chamber to 3%-10% for NMHC, with negligible effects for NOx.

Another cause of excess engine-out HC emissions is the combustion of lubricating oil that leaks into the combustion chamber, since heavier hydrocarbons in oil do not oxidize as readily as those in gasoline. Oil in the combustion chamber can also trap gaseous HC from the fuel and release it later unburned. In addition, some components in lubricating oil can poison the catalyst and reduce its effectiveness. To reduce oil consumption, vehicle manufacturers will tighten tolerances and improve surface finishes for cylinders and pistons, improve piston ring design and material, and improve exhaust valve stem seals to prevent excessive leakage of lubricating oil into the combustion chamber. According to CARB and EEA, virtually all vehicles meeting LEV and ULEV standards, will have to incorporate features to reduce oil consumption.

As discussed above, engine-out NOx emissions result from high combustion temperatures. Therefore, the main control strategies for reducing engine-out NOx are designed to lower combustion temperature. The most promising techniques for reducing combustion temperatures, and thus engine-out NOx emissions, are the combination of increasing the rate of combustion, reducing spark advance, and adding a diluent to the air-fuel mixture, typically via exhaust gas recirculation. The rate of combustion can be increased by using "fast burn" combustion chamber designs. A fast burn combustion rate provides improved thermal efficiency and a greater tolerance for dilution from EGR resulting in better fuel economy and lower NOx emissions. There are numerous ways to design a fast burn combustion chamber. However, the most common approach is to induce turbulence into the combustion chamber which increases the surface area of the flame front and thereby increases the rate of combustion, and to locate the spark plug in the center of the combustion chamber. Locating the spark plug in the center of the combustion chamber promotes more thorough combustion and allows the ignition timing to be retarded, decreasing the dwell time of hot gases in the combustion chamber and reducing NOx formation. According to CARB and EEA, most vehicle manufacturers induce turbulence into the combustion chamber by increasing the velocity of the incoming air-fuel mixture and having it enter the chamber in a swirling motion (known as "swirl").

2. Improved EGR Design

One of the most effective means of reducing engine-out NOx emissions is exhaust gas recirculation. By recirculating spent exhaust gases into the combustion chamber, the overall air-fuel mixture is diluted, lowering peak combustion temperatures and reducing NOx. As discussed above, the use of high swirl, high turbulence combustion chambers can allow the amount of EGR to be increased from current levels of 15 to 17 percent to levels possibly as high as 20 to 25[6] percent, resulting in a 15 to 20 percent reduction in engine-out NOx emissions.

Many EGR systems in today's vehicles utilize a control valve that requires vacuum from the intake manifold to regulate EGR flow. Under part-throttle operation where EGR is needed, engine vacuum is sufficient to open the valve. However, during throttle applications near or at wide-open throttle, engine vacuum is too low to open the EGR valve. While EGR operation only during part-throttle driving conditions has been sufficient to control NOx emissions for most vehicles in the past, more stringent NOx standards and emphasis on controlling off-cycle emission levels may require more precise EGR control and additional EGR during heavy throttle operation to reduce NOx emissions. Many manufacturers now use electronic EGR in place of mechanical back-pressure designs. By using electronic solenoids to open and close the EGR valve, the flow of EGR can be more precisely controlled.

CARB projects that all LEV and ULEV vehicles will utilize electronic EGR systems in lieu of mechanical systems. While most manufacturers agree that electronic EGR gives more precise control of EGR flow rate, not all manufacturers are using it. Numerous LEV vehicles certified for the 1998 model year still use mechanical EGR systems, and in some cases, no EGR at all. Nonetheless, the use of EGR remains a very important tool in reducing engine-out NOx emissions, whether mechanical or electronic.

3. Multiple Valves and Variable-Valve Timing

Conventional engines have two valves per cylinder, one for intake of the air-fuel mixture and the other for exhaust of the combusted mixture. The duration and lift (distance the valve head is pushed away from its seat) of valve openings is constant regardless of engine speed. As engine speed increases, the aerodynamic resistance to pumping air in and out of the cylinder for intake and exhaust also increases. By doubling the number of intake and exhaust valves, pumping losses are reduced, improving the volumetric efficiency and useful power output.

In addition to gains in breathing, the multiple-valve (typically 4-valve) design allows the spark plug to be positioned closer to the center of the combustion chamber (as discussed above) which decreases the distance the flame must travel inside the chamber. In addition, the two streams of incoming gas can be used to achieve greater mixing of air and fuel, further increasing

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6 Some manufacturers have stated that EGR impacts the ability to control net air-fuel ratios tightly due to dynamic changes in exhaust back pressure and temperature, and that the advantages of increasing EGR flow rates are lost partly in losses in air-fuel ratio control even with electronic control of EGR. Higher EGR flow rates can be tolerated by modern engines with more advanced combustion chambers, but EGR cooling may be necessary to achieve higher EGR flow rates within acceptable detonation limits without significant loss of air-fuel control.

combustion efficiency which lowers engine-out HC emissions.

Even greater improvements to combustion efficiency can be realized by using valve timing and lift control to take advantage of the 4-valve configuration. Conventional engines utilize fixed-valve timing and lift across all engine speeds. Typically the valve timing is set at a level that is a compromise between low speed torque and high engine speed horsepower. At light engine loads it would be desirable to close the intake valve earlier to reduce pumping losses. Variable valve timing can enhance both low speed torque and high speed horsepower with no necessary compromise between the two. Variable valve timing can allow for increased swirl and intake charge velocity, especially during low load operating conditions where sufficient swirl and turbulence tend to be lacking. By providing a strong swirl formation in the combustion chamber, the air-fuel mixture can mix sufficiently, resulting in a faster, more complete combustion, even under lean air-fuel conditions, thereby reducing emissions. Variable valve technology by itself may have somewhat limited effect on reducing emissions. Several vehicle manufacturers estimate emission reductions of 3%-10% for both, NMHC and NOX, but reductions could be increased when variable valve timing is combined with optimized spark plug location and additional EGR.

Multi-valve engines already exist in numerous federal and California certified vehicles and are projected by CARB to become even more common. CARB also projects that in order to meet LEV and ULEV standards, more vehicles will have to make improvements to the induction system, including the use of variable valve timing.

4. Leak-Free Exhaust System

Leaks in the exhaust system can result in increased emissions, but not necessarily from emissions escaping from the exhaust leak to the atmosphere. With an exhaust system leak, ambient air is typically sucked into the exhaust system by the pressure difference created by the flowing exhaust gases inside the exhaust pipe. The air that is sucked into the exhaust system is unmetered and, therefore, unaccounted for in the fuel system's closed-loop feedback control, resulting in erratic and/or overly rich fuel control. This results in increased emission levels and potentially poor drive ability. In addition, an air leak can cause an oxidation environment to exist in a three-way catalyst at low speeds that would hamper reduction of NOX and lead to increased NOX emissions.

Some vehicles currently use leak-free exhaust systems today. These systems consist of an improved exhaust manifold/exhaust pipe interface plus a corrosion-free flexible coupling inserted between the exhaust manifold flange and the catalyst to reduce stress and the tendency for leakage to occur at the joint. In addition, improvements to the welding process for catalytic converter canning could ensure less air leakage into the converter and provide reduced emissions. CARB and EEA project that vehicle manufacturers will continue to incorporate leak-free exhaust systems as emission standards become more stringent.

B. Improvements in Air-Fuel Ratio Control

Modern three-way catalysts require the air-fuel ratio (A/F) to be as close to stoichiometric operation (the amount of air and fuel just sufficient for nearly complete combustion) as possible. This is because three-way catalysts simultaneously oxidize HC and CO, and reduce NOx. Since HC and CO are oxidized during A/F operation slightly lean of stoichiometry, while NOx is reduced during operation slightly rich of stoichiometry, there exists a very small A/F window of operation around stoichiometry where catalyst conversion efficiency is maximized for all three pollutants (i.e., less than 1% deviation in A/F or roughly ± 0.15). Contemporary vehicles have been able to maintain stoichiometric, or very close to it, operation by using closed-loop feedback fuel control systems. At the heart of these systems has been a single heated exhaust gas oxygen (HEGO) sensor. The HEGO sensor continuously switches between rich and lean readings. By maintaining an equal number of rich readings with lean readings over a given period, the fuel control system is able to maintain stoichiometry. While this fuel control system is capable of maintaining the A/F with the required accuracy under steady-state operating conditions, the system accuracy is challenged during transient operation where rapidly changing throttle conditions occur. Also, as the sensor ages, its accuracy decreases.

1. Dual Oxygen Sensors

Many vehicle manufacturers have placed a second HEGO sensor(s) downstream of one or more catalysts in the exhaust system as a method for monitoring the catalyst effectiveness of the federally and California mandated on-board diagnostic (OBD II) system. In addition to monitoring the effectiveness of the catalyst, the downstream sensors can also be used to monitor the primary control sensor and adjust for deterioration, thereby maintaining precise A/F control at higher mileages. Should the front primary HEGO sensor, which operates in a higher temperature environment, begin to exhibit slow response or drift from its calibration point, the secondary downstream sensor can be relied upon for modifying the fuel system controls to compensate for the aging effects. By placing the second sensor further downstream from the hot engine exhaust, where it is also less susceptible to poisoning, the rear sensor is less susceptible to aging over the life of the vehicle. As a result, the use of a dual oxygen sensor fuel control system can ensure more robust and precise fuel control, resulting in lower emissions.

Currently, all vehicle manufacturers use a dual oxygen sensor system for monitoring the catalyst as part of the OBD II system. As discussed above, most manufacturers also utilize the secondary HEGO sensor for trim (i.e., adjustments to) of the fuel control system. It is anticipated that all manufacturers will soon use the secondary sensor for fuel trim.

2. Universal Oxygen Sensors

The universal exhaust gas oxygen (UEGO) sensor, also called a "linear oxygen sensor”, could replace conventional HEGO sensors. Conventional HEGO sensors only determine if an engine's A/F is richer or leaner than stoichiometric, providing no indication of what the magnitude of the A/F actually is. In contrast, UEGO's are capable of recognizing both the direction and magnitude of A/F transients since the voltage output of the UEGO is "proportional" with changing A/F (i.e., each voltage value corresponds to a certain A/F). Therefore, proportional A/F control is possible with the use of UEGO sensors, facilitating faster response of the fuel feedback control system and tighter control of A/F. Some vehicle manufacturers have estimated emission reductions attributed to the use of a UEGO sensor to be 5% for NMHC and 23%-35% for NOx. EPA feels that the estimate for NMHC seems low.

Although some manufacturers are currently using UEGO sensors, EEA claims that some manufacturers are of mixed opinion as to the future applicability of UEGO sensors. Because of their high cost, manufacturers claim that it may be cheaper to improve HEGO technology rather than utilize UEGO sensors. An example of this is the use of a "planar" design for HEGO sensors. Planar HEGO sensors have a thimble design that is considerably lighter than conventional designs. The main benefits are faster heat-up time and sensor response.

3. Individual Cylinder A/F Control

Another method for tightening fuel control is to control the A/F in each individual cylinder. Current fuel control systems control the A/F for the entire engine or a bank of cylinders. By controlling A/F for the entire engine or a bank of cylinders, any necessary adjustments made to fuel delivery for the engine are applied to all cylinders simultaneously, regardless of whether all cylinders need the that amount of fuel delivered. For example, there is usually some deviation in A/F between cylinders. If a particular cylinder is rich, but the "bulk" A/F indication for the engine is lean, the fuel control system will simultaneously increase the amount of fuel delivered to all of the cylinders, including the rich cylinder. Thus, the rich cylinder becomes even richer having a potentially negative effect on the net A/F.

Individual cylinder A/F control helps diminish variation among individual cylinders. This is accomplished by modeling the behavior of the exhaust gases in the exhaust manifold and using sophisticated software algorithms to predict individual cylinder A/F. Individual cylinder A/F control requires use of an UEGO sensor in lieu of the traditional HEGO sensor, and requires a more powerful engine control computer. Some vehicle manufacturers have estimated the potential emission reductions for individual cylinder A/F control to 22% for NMHC and 3% for NOx, but EPA feels that based on conversations with other manufacturers, that the estimate for NOx reduction is too low.

4. Adaptive Fuel Control Systems

The fuel control systems of virtually all current vehicles incorporate a feature known as "adaptive memory" or "adaptive block learn." Adaptive fuel control systems automatically adjust the amount of fuel delivered to compensate for component tolerances, component wear, varying environmental conditions, varying fuel compositions, etc., to more closely maintain proper fuel control under various operating conditions.

For most fuel control systems in use today, the adaption process affects only steady-state operation conditions (i.e., constant or slowly changing throttle conditions). Because transient operating conditions have always provided a challenge to maintaining precise fuel control, the use of adaptive fuel control for transient operation would be extremely valuable. Accurate fuel control during transient driving conditions has traditionally been difficult because of inaccuracies in predicting the air and fuel flow under rapidly changing throttle conditions. Air and fuel dynamics within the intake manifold (fuel evaporation and air flow behavior), and the time delay between measurement of air flow and the injection of the calculated fuel mass, result in temporarily lean A/F during transient operation. Variation in fuel properties, particularly distillation characteristics, also increases the difficulty in predicting A/F during transients. These can all lead to poor drive ability and an increase in NOx emissions.

Adaptive transient fuel control is already being utilized by some manufacturers across their entire product line. CARB expects the use of adaptive transient fuel control to be incorporated in virtually all LEVs and ULEVs.

5. Electronic Throttle Control Systems

As mentioned above, the time delay between the air mass measurement and the calculated fuel delivery presents one of the primary difficulties in maintaining accurate fuel control and good drive ability during transient driving conditions. With the conventional mechanical throttle system (a metal linkage connected from the accelerator pedal to the throttle blade in the throttle body), quick throttle openings can result in a lean A/F spike in the combustion chamber. Although algorithms can be developed to model air and fuel flow dynamics to compensate for these time delay effects, the use of an electronic throttle control system, known as “drive-by-wire” or “throttle-by-wire,” may better synchronize the air and fuel flow to achieve proper fueling during transients (e.g., the driver moves the throttle, but the fuel delivery is momentarily delayed to match the inertial lag of the increased airflow).

While this technology is currently used in several vehicle models, it is considered expensive and those vehicles equipped with the feature are expensive higher end vehicles. Because of its high cost, it is not anticipated that drive-by-wire technology will become commonplace in the near future.

C. Improvements in Fuel Atomization

In addition to maintaining a stoichiometric A/F ratio, it is also important that a homogeneous air-fuel mixture be delivered at the proper time and that the mixture is finely atomized to provide the best combustion characteristics and lowest emissions. Poorly prepared air-fuel mixtures, especially after a cold start and during the warm-up phase of the engine, result in significantly higher emissions of unburned HC since combustion of the mixture is less complete. By providing better fuel atomization, more efficient combustion can be attained, which should aid in improving fuel economy and reducing emissions. Sequential multi-point fuel injection and air-assisted fuel injectors are examples of the most promising technologies available for improving fuel atomization.

1. Sequential Multi-Point

Typically, conventional multi-point fuel injection systems inject fuel into the intake manifold by injector pairs. This means that rather than injecting fuel into each individual cylinder, a pair of injectors (or even a whole bank of injectors) fires simultaneously into several cylinders. Since only one of the cylinders is actually ready for fuel at the moment of injection, the other cylinder(s) gets too much or too little fuel. With this less than optimum fuel injection timing, fuel puddling and intake manifold wall wetting can occur, both of which can hinder complete combustion. Sequential injection, on the other hand, delivers a more precise amount of fuel that is required by each cylinder to each cylinder at the appropriate time. Because of the emission reductions and other performance benefits “timed” fuel injection offers, sequential fuel injection systems are very common on today’s vehicles and are expected to be incorporated in all vehicles soon.

2. Air-Assisted Fuel Injectors

Another method to further homogenize the air-fuel mixture is through the use of air-assisted fuel injection. By injecting high pressure air into the fuel injector, and subsequently, the fuel spray, greater atomization of the fuel droplets can occur. Since achieving good fuel atomization is difficult when the air flow into the engine is low, air-assisted fuel injection can be particularly beneficial in reducing emissions at low engine speeds. In addition, industry studies have shown that the short burst of additional fuel needed for responsive, smooth transient maneuvers can be reduced significantly with air-assisted fuel injection due to a decrease in wall wetting in the intake manifold. EEA estimates a reduction in NMHC emissions of 3%-10% for air-assisted fuel injection. At least three manufacturers are currently using air-assisted injection in some of their models.

D. Improvements to Exhaust Aftertreatment Systems

Over the last five years or so, there have been tremendous advancements in exhaust aftertreatment systems. Catalyst manufacturers are progressively moving to palladium (Pd) as the main precious metal in automotive catalyst applications. Improvements to catalyst thermal stability and washcoat technologies, the design of higher cell densities, and the use of two-layer washcoat applications are just some of the advancements made to catalyst technology. There has also been much development in HC and NOx absorber technology. The advancements to exhaust aftertreatment systems are probably the single most important area of emission control development.

1. Catalysts

As previously mentioned, significant changes in catalyst formulation, size and design have been made in recent years and additional advances in these areas are still possible. Palladium is likely to continue as the noble metal of choice for close-coupled applications and will start to see more use in underfloor applications. Palladium catalysts, however, are less resistant to poisoning by oil-and fuel-based additives than conventional platinum/rhodium (Pt/Rh) catalysts. Based on current certification trends and information from EEA, it is expected that Pd catalysts will be used in the close-coupled locations while conventional or tri-metal (Pd/Pt/Rh) catalysts will continue to be used in underfloor applications. Some manufacturers have suggested that they will use Pd/Rh in lieu of tri-metal or conventional Pt/Rh catalysts for underfloor applications. As palladium technology continues to improve, it may be possible for a single close-coupled catalyst to replace both catalysts. If fact, at least one vehicle manufacturer currently uses a single Pd-only catalyst for one of their models. According to EEA, new Pd-only catalysts are now capable of withstanding exposure to temperatures as high as 1050°C and, as a result, can be moved very close to the exhaust manifold to enhance catalyst light-off performance.

In addition to reliance on Pd and tri-metal applications, catalyst and vehicle manufacturers have developed “layered” catalysts. Typically, conventional catalysts have a single washcoat layer applied to the catalyst substrate. The washcoat is the material that contains the noble metals and numerous other substances such as base metals, stabilizers, etc. By applying the washcoat in layers (one layer on top of another) and using slightly different washcoat and noble metal formulations for the various layers, manufacturers have found that emissions can be further reduced from single layer applications and, in some cases, reduced significantly.

Manufacturers are developing catalysts with substrates that utilize thinner walls in order to design higher cell density, low thermal mass catalysts for close-coupled applications (improves mass transfer at high engine loads and increase catalyst surface area). The cells are coated with washcoat which contain the noble metals which perform the catalysis on the exhaust pollutants. The greater the number of cells, the more surface area with washcoat that exists, meaning there is more of the catalyst available to convert emissions (or that the same catalyst surface area can be put into a smaller volume). Cell densities of 600 cells per square inch (cpsi) have already been commercialized, and research on 900 cpsi catalysts has been progressing. Typical cell densities for conventional catalysts are 400 cpsi.

The largest source for HC continues to be from cold start operation where the combination of rich A/F operation and the ineffectiveness of a still relatively cool catalyst result in excess HC emissions. One of the most effective strategies for controlling cold start HC emissions is to reduce the time it takes to increase the operating temperature of the catalyst immediately following engine start-up. The effectiveness or efficiency of the catalyst increases as the catalyst temperature increases. One common strategy is to move the catalyst closer to the exhaust manifold where the exhaust temperature is greater (a close-coupled catalyst). Another strategy is to use an electrically-heated catalyst. The EHC consists of a small electrically heated catalyst placed directly in front of a conventional catalyst. Both substrates are located in a single can or container. The EHC is powered by the alternator, or solely from the vehicle's battery, or from a combination of the alternator and battery. The EHC is capable of heating up almost immediately, assisting the catalyst that directly follows it to also heat up and obtain light-off temperature (the catalyst temperature where catalyst efficiency is 50%) quickly. Manufacturers indicate that EHCs will probably only be necessary for a limited number of LEV/ULEV engine families, mostly larger displacement V-8s where cold start emissions are difficult to control. According to EEA, EHCs can reduce NMHC emissions by $\geq$10% and NOx emissions by 5%-10%, and with continuing improvements in conventional catalyst light-off time, thermal durability, and overall activity, EHCs will become unnecessary for any vehicle to meet the LEV/ULEV standards the next few years.

2. Adsorbers/Traps

Other potential exhaust aftertreatment systems that are used in conjunction with a catalyst or catalysts, are the HC and NOX adsorbers/traps. Hydrocarbon adsorbers are designed to trap HC while the catalyst is cold and unable to sufficiently convert the HC. They accomplish this by utilizing an adsorbing material that holds onto the HC. Once the catalyst is warmed up, the trapped HC are released from the adsorption material and directed to the fully functioning downstream three-way catalyst. There are three principal methods for incorporating the adsorber into the exhaust system. The first is to coat the adsorber directly on the catalyst substrate. The advantage is that there are no changes to the exhaust system required, but the desorption process cannot be easily controlled and usually occurs before the catalyst has reached light-off temperature. The second method locates the adsorber in another exhaust pipe parallel with the main exhaust pipe, but in front of the catalyst and includes a series of valves that route the exhaust through the adsorber in the first few seconds after cold start, switching exhaust flow through the catalyst thereafter. Under this system, mechanisms to purge the trap are also required. The third method places the trap at the end of the exhaust system, in another exhaust pipe parallel to the muffler, because of the low thermal tolerance of adsorber material. Again, a purging mechanism is required to purge the adsorbed HC back into the catalyst, but adsorber overheating is avoided. Several vehicle manufacturers estimate reductions in HC of greater than 10%.

NOX adsorbers have been researched, but, according to EEA, are generally recognized as a control for NOx resulting from reduced EGR. They are typically used for lean-burn applications and are not applicable to engines that attempt to maintain stoichiometry all the time.

3. Secondary Air Injection

Secondary injection of air into exhaust ports after cold start when the engine is operating rich, coupled with spark retard, can promote combustion of unburned HC and CO in the exhaust manifold and increase the warm-up rate of the catalyst. This is one of the oldest and most established emission control technologies in use, yet over the past 5 to10 years it has disappeared from most vehicles, except for those with the largest displacement engines. With LEV and ULEV requirements, however, secondary air is again becoming a valuable emission control technology, especially in conjunction with EHC's and adsorbers.

4. Insulated or Dual Wall Exhaust System

Insulating the exhaust system is another method of furnishing heat to the catalyst to decrease light-off time. Similar to close-coupled catalysts, the principle behind insulating the exhaust system is to conserve heat generated in the engine for aiding the catalyst warm-up. Through the use of laminated thin-wall exhaust pipes, less heat will be lost in the exhaust system, enabling quicker catalyst light-off. CARB projects that all LEV and ULEV vehicles will utilize insulted exhaust systems, however, EEA claims that as catalyst technology advances and the catalyst is moved closer to the engine, the benefits of insulated exhaust systems diminish rapidly.

E. Improvements in Engine Calibration Techniques

Of all the technologies discussed above, one of the most important emission control strategies is not hardware-related. Rather, it's the software and, more specifically, the algorithms and calibrations contained within the software that are used in the power-train control module (PCM) which control how the various engine and emission control components and systems operate. Advancements in software along with refinements to existing algorithms and calibrations can have a major impact in reducing emissions. Confidential discussions between manufacturers and EPA suggest that manufacturers believe emissions can be further reduced by improving and updating their calibration techniques. As computer technology and software continues to advance, so does the ability of the automotive engineer to use these advancements in ways to better optimize the emission control systems. For example, as processors become faster, it is possible to perform calculations quicker, thus allowing for faster response times for things such as fuel and spark control. As the PCM becomes more powerful with greater memory capability, algorithms can become more sophisticated. Manufacturers have found that as computer processors, engine control sensors and actuators, and computer software become more advanced, and, in conjunction with their growing experience with developing calibrations, as time passes, their calibration skills will continue to become more refined and robust, resulting in even lower emissions.

Manufacturers have suggested to EPA that perhaps the single most effective method for controlling NOx emissions will be tighter A/F control which could be accomplished with advancements in calibration techniques without necessarily having to use advanced technologies, such as UEGO sensors. Manufacturers have found ways to improve calibration strategies such that meeting federal cold CO requirements, as well as, complying with LEV standards, have not required the use of advanced hardware, such as EHCs or adsorbers.

Since emission control calibrations are typically confidential, it is difficult to predict what advancements will occur in the future, but it is clear that improved calibration techniques and strategies are a very important and viable method for further reducing emissions.

F. Particulate Emissions

Particulate emissions from gasoline-fueled vehicles consists of both carbon- and sulfur-containing compounds. The carbonaceous particulate is produced from both the gasoline fuel and engine lubricating oil. Available data indicate that particulate emissions are highest during cold starts, and lower during hot starts and warmed up operation.

Technology aimed at reducing gaseous NMHC emissions tends to reduce carbonaceous particulate emissions, as well. Examples are modifications to pistons and rings to reduce oil consumption, close-coupled catalysts to reduce cold start emissions, advanced catalyst technology and improved air-fuel ratio control. EPA is not aware of any particulate emission control techniques for gasoline vehicles that is not also being considered for NMHC emission control. As indicated in the previous chapter, the need to reduce NMHC emissions from gasoline vehicles appears to be greater than the need to reduce carbonaceous particulate emissions. Therefore, carbonaceous particulate emission control from gasoline vehicles will likely accompany required NMHC emission control.

The predominant form of sulfur-containing particulate from motor vehicles is sulfuric acid (commonly referred to as sulfate). This sulfate is produced in both the engine and the exhaust system by the oxidation of sulfur dioxide. The amount of sulfate emissions is generally directly proportional to the amount of sulfur in the fuel, though more than 98% of the fuel sulfur is emitted as sulfur dioxide. Sulfate emissions can also be affected by the air-fuel ratio of the engine and the type of catalyst employed. The addition of excess air into an oxidation catalyst can especially increase sulfate emissions. However, the current approach of operating engines as close to stoichiometric as possible coupled with advanced three-way catalysts appears to keep sulfate emissions at very low levels. Therefore, the primary technique available for reducing sulfate emissions is to reduce gasoline sulfur levels.

Diesel particulate emissions also consist of both carbonaceous and sulfate particulate. Unlike gasoline emissions, carbonaceous particulate and NMHC emissions from a diesel engine are not as directly related. Engine-related techniques for reducing particulate emissions include higher fuel injection pressures, electronic engine control of injection timing, rate and duration, and turbo charging/aftercooling. Exhaust aftertreatment techniques include the use of an oxidation catalyst or a trap. The oxidation catalyst primarily reduces the heavy organic portion of the carbonaceous particulate, which usually represents 30-50% of total carbonaceous particulate emissions. Traps can reduce both organic and solid carbon particulate and are capable of controlling 70-90% of carbonaceous particulate emissions.

Diesel-powered LDVs and LDTs produced in the late 1980s were capable of meeting particulate emission standards in the range of 0.1-0.2 g/mi without the use of exhaust aftertreatment. One manufacturers also produced some vehicles equipped with traps. A few light-duty diesel models are currently being certified to the current Tier 1 standards of 0.1-0.12 g/mi without the need for aftertreatment.

Sulfate emissions from a diesel engine form primarily in the engine and generally represent 2% of the total sulfur in the fuel. The primary method to reduce sulfate emissions is to reduce the sulfur content of diesel fuel. The use of an oxidation catalyst or a catalyst-containing trap can increase sulfate emissions.

G. Advanced Technology

Thus far, the technology assessment performed in *Chapter VI. Regulatory Issues* and *Appendix B. Vehicle Technology*, focused on conventional emission control technology for vehicles with gasoline-powered spark ignition engines. There are a number of advanced technologies in the near horizon that may be capable even further reductions in emissions. Examples of such technologies are fuel cells, electric vehicles, and hybrid vehicles.

Fuel cell technology converts such fuels as methanol, natural gas, and gasoline into electrical energy without generating the pollutants associated with internal-combustion engines. A fuel cell is made of a thin plastic film sandwiched between two plates. Hydrogen fuel and oxygen from the air are electrically combined in the fuel cell to produce electricity. Typically, the only by-products are heat and water vapor. A fuel cell coupled with an electrically powered drive-train is essentially a quite, zero-emissions vehicle.

Electric vehicles use electric motors to power the wheels. The electric motors are powered by packs of batteries stored underneath the vehicle. These vehicles use many newer technologies, such as advanced charging and regenerating systems as well as vehicle structural design. Battery technology, which has been the major technical limitation to date, has been and will be the focus of much developmental work. Improved nickel-metal hydride and lithium ion batteries are two of the battery types being analyzed for use in electric vehicles produced in the near future.

Hybrid vehicles are typically powered by a combination of two powertrain systems. There is usually a low or zero emitting main powertrain system (e.g., battery-powered electric motors) that powers the vehicle during steady-state operation, when power demands are low. When more power is required to accelerate or drive up a hill, an axillary powertrain, usually a small displacement internal combustion engine is used. The engine may be diesel-powered, or some derivative thereof, or an alternative-fuel powered spark ignition engine that is low emitting. Because the engine used is small and low polluting, and the majority of operation uses the non-engine powertrain, hybrid vehicles have the potential to be very low emitting vehicles.

Appendix C

EMISSION REDUCTIONS, COSTS AND COST EFFECTIVENESS

The discussion in *Appendix B. Vehicle Technology* demonstrates that there are numerous emission control technologies currently available, and, in many cases in use, capable of reducing emissions below Tier 1 standards. The purpose of this appendix is to expand upon the discussion in *Chapter V. Assessment of Coast and Cost Effectiveness* on estimating the emission benefits and costs associated with emission control technologies capable of reducing emissions below Tier 1 standards.

As discussed earlier, the sources for the benefits and costs of the various emission control technologies were the EEA report, the CARB report, MECA, API and confidential information from vehicle manufacturers. Of these sources, only EEA, CARB and several vehicle manufacturers supplied information on costs. Consequently, these are the sources that are primarily used for establishing cost effectiveness.

It was also stated earlier that it was not necessary to incorporate all of the technologies discussed above in order to produce vehicles capable of emitting below Tier 1 levels. The choices and combinations of technologies will depend on several factors, such as current engine-out emission levels, effectiveness of current emission control technologies, and individual manufacturer preferences. It was noted that there are four technological areas that have the greatest potential for further reducing emissions. For the purposes of this study, EPA will present estimates for emission benefits and costs using six technological approaches.

- Improved A/F control
- Increased catalyst volume and loading
- Improved catalyst washcoat/substrate designs
- Close-coupled catalyst
- Advanced catalyst design
- Increased EGR rates

These technologies are the main technologies being used by vehicle manufacturers to meet LEV, and soon, National LEV standards. Although there are currently only a few vehicles certified to ULEV standards (one of which is a compressed natural gas vehicles), it is anticipated that these same technologies will be used to meet ULEV requirements as well. The LEV standards represent a reduction (from Tier 1 standards) of 70% for NMHC and 50% for NOx. The default Tier 2 standards represent a 50% reduction for NMHC and NOx, respectively, while the ULEV standards represent a 84% reduction in NMHC and a 50% reduction in NOx. The emission reduction estimates used in the study, and based on the above six technologies, results in emission reductions of up to 77% for NMHC and up to 80% for NOx.

For the purposes of this study, EPA projects that tighter A/F ratio control can be achieved by using a combination of faster response fuel injectors, a faster PCM microprocessor, improved HEGO sensor design (planar design), the use of dual HEGO sensors and adaptive transient fuel control, and improved calibration strategies. The estimates of emission benefits for tighter A/F control through the use of the technologies/strategies vary. Information from MECA and two vehicle manufacturers suggest that NOx emission benefits can range from 20% to 70%, while EEA estimated emission reductions of greater than 10% (no upper limit was provided) for HC and NOx. They stressed, however, that the upper range of the estimates could only be achieved through more sophisticated calibration strategies used in conjunction with the above mentioned technology, and that these strategies were not yet available. Based on this information, EPA projects that the emission benefits resulting from tighter A/F control to be 10% for NMHC and 20% for NOx.

Estimates for emission benefits of modest increases in catalyst loading and volume were consistent among the various sources. EEA estimates a benefit of 10% for HC and 10% or greater for NOx. MECA and several vehicle manufacturers concurred with these estimates. Thus, EPA projected a benefit of 10% for NMHC and 20% for NOx. For improvements to catalyst formulations and substrate designs, the estimates were a consensus of 10% for HC and NOx. Therefore, EPA projected benefits of 10% for both NMHC and NOx. The benefits of using a close-coupled catalyst were estimated by various vehicle manufacturers to range from 50% to 70% for HC, while estimates for NOx were lower at approximately 10%. EPA projected the emission benefits for close-coupled catalysts at 50% for NMHC and 10% for NOx. Finally, information from the American Petroleum Institute suggested that for catalysts utilizing advanced (tri-metal and multi-layer) designs, emission reductions ranging from 20% to 37% can be achieved for HC and 30% to 50% for NOx. EPA projected advanced catalyst design emission benefits of 37% for NMHC and 50% for NOx.

EEA estimated the emission benefit for increased EGR rates (most likely occurring from the use of electronic EGR) to be 10% or greater for NOx (EGR does not reduce NMHC or CO). Several vehicle manufacturers also indicated that increased EGR could result in reductions of 10% or greater. Based on this information, EPA has projected NOx emission benefit resulting from increased EGR rates to be 20%.

The total emission benefits estimated by EPA for tighter A/F control, improvements to catalyst designs, and increased EGR rates, as mentioned earlier, are up to 77% for NMHC and up to 80% for NOx. Table C.1 lists the projected Tier 2 technologies used in the study and their associated emission reductions.

Table C.1 List of Potential Tier 2 Technologies and Associated Emission Reductions

Technology	Percent Emission Reduction	
	NMHC	NOx
Improved A/F Control	10%	20%

Increased Catalyst Volume and Loading	10%	20%
Improved Catalyst Washcoat/Sustrate	10%	10%
Close-Coupled Catalyst	50%	10%
Advanced Catalyst Design	37%	50%
Increased EGR	0%	20%
Total	77%	80%

These estimates were determined by combining the percent emission reduction for the respective technologies in a multiplicative fashion as seen below.

NMHC = 100% - (100%-10%)*(100%-10%)*(100%-10%)*(100%-50%)*(100%-37%)*(100%-0%) = 77%

NOx = 100% - (100%-20%)*(100%-20%)*(100%-10%)*(100%-10%)*(100%-50%)*(100%-20%) = 80%

Table C.2 lists the estimated costs for the respective technologies. Cost estimates are presented for NMHC, NOx, and NMHC+NOx for LDV and LDT. The costs associated with each technology are estimates of the manufacturing costs. In assessing the cost to consumers of emission control equipment, EPA uses a "markup" approach to estimate the retail price equivalent (RPE) for an emission control component from an estimate of the component's direct manufacturing cost. Given this methodology, the difference between the RPE and the direct manufacturing cost includes allocated overhead costs, profit margins, and other indirect cost estimates at several stages in the production and marketing process. The current RPE factor being used by EPA is 1.26. The last row of table C.2 is the total estimated retail price equivalent cost (i.e., total manufacturing cost x RPE factor (1.26)).

Table C.2 Estimated Costs for Respective Technologies

	Cost per vehicle ($)					
	LDV			LDT		
Technology	NMHC	NOx	NMHC+ NOx	NMHC	NOx	NMHC+ NOx
Improved A/F Control	$2.65	$2.65	$5.30	$3.05	$3.05	$6.10
Increased Catalyst Volume and Loading	$6.50	$6.50	$13.00	$7.60	$7.60	$15.20

Improved Catalyst Washcoat/Sustrate	$6.20	$6.20	$12.40	$7.20	$7.20	$14.40
Close-Coupled Catalyst	$10.15	$10.15	$20.30	$10.15	$10.15	$20.30
Advanced Catalyst Design	$20.00	$20.00	$40.00	$27.50	$27.50	$55.00
Increased EGR	$0.00	$17.00	$17.00	$0.00	$17.00	$17.00
Total	$45.50	$62.50	$108.00	$55.50	$72.50	$128.00
Total x RPE (1.26)	$57.33	$78.75	$136.05	$69.93	$91.35	$161.28

All cost estimates are based on information supplied by EEA, CARB, and various vehicle manufacturers. For all of the technologies except increased EGR, cost estimates are dependant upon engine size. As engine size increases, so do costs. Engine size was defined as 4-cylinder, 6-cylinder, and 8-cylinder. A single cost estimate for each technology was developed by weighting the three individual costs by 1996 sales. Because costs for 4-cylinder technologies is lower, combined with the fact that LDVs have a higher percentage of 4-cylinder engines, LDVs have lower costs than LDTs. Conversely, because larger engines have higher costs, and LDTs have a higher percentage of large engines, LDTs have higher costs than LDVs.

EEA estimated the cost of improved A/F control to be $10.60 for LDV and $12.20 for LDT, while CARB estimated this action could be done at little or no additional cost, because they argued that improvements to A/F would only constitute software changes only with no additional hardware cost. EPA feels that some level of hardware will be necessary, but agrees with CARB that a significant portion of improvements made to A/F control will result from improvements to fuel control calibrations. Therefore, EPA estimated the cost of A/F control to be the average of the EEA and CARB estimates, or $5.30 for LDV and $6.10 for LDT. Note that CARB has estimated a cost of $8-12 per vehicle for improved fuel preparation such as air-assisted injection.

The cost estimates for increased catalyst volume and loading, as well as improvements to catalyst washcoat and substrate, were taken directly from EEA estimates and were $13.00 for LDVs and $15.20 for LDTs and $12.40 for LDVs and $15.20 for LDTs, respectively.

Cost estimates for close-coupled catalysts came from CARB. They estimated the cost to be the same for all engine sizes, however, they estimated that a number of Tier 1 vehicles equipped with 4-cylinder engines already use close-coupled catalysts. Therefore, the incremental cost for 4-cylinder engines is less than for the larger engines.

Estimates for increased EGR rates came directly from EEA. However, as stated above, costs for EGR were the same for all engine sizes and were not sales weighted.

Cost Effectiveness Calculation

EPA estimated the costs and emissions benefits on a per vehicle basis. Cost effectiveness is represented as the dollar cost per ton of emissions reduced ($/ton). The cost component, the numerator, is taken directly from the above discussion of vehicle costs, using $136 per vehicle for LDVs and $161 for LDTs.

Conceptually, the benefit calculation is derived by taking an estimate of in-use emissions for Tier 1 vehicles and applying the percent reduction estimates of 77% for NMHC and 80% for NOx. The resulting benefit is thus the difference between the Tier 1 level and the “Tier 2 control” level.

The Tier 1 in-use level is based on the modified version of MOBILE5 discussed in Appendix A. The CALIMFAC zero mile emission factor and average in-use deterioration factor[7] were adjusted for the effect of off-cycle driving patterns on emissions (Step 1). The resulting Tier 1 in-use emission rate is then multiplied by the percent emission reductions estimated for Tier 2 controls, 77% for NMHC and 80% for NOx . The emission benefit is the difference between the Tier 1 level and Tier 2 control level (Step 2).

The next step is to convert the gram per mile emission benefit into a per vehicle lifetime emission benefit. This is achieved by multiplying the gram per mile emission benefit by average lifetime miles. The lifetime miles are discounted using a standard discount rate of seven percent in order to discount the emission benefits by the number of years in the future in which they are realized.[8] The last step is to convert the grams into tons (Step 3). Dividing the per vehicle cost by the per vehicle emission benefits yields the dollar per ton cost effectiveness estimate (Step 4).

Step 1: (Zero mile emission rate + (deterioration rate * average mileage))*(off-cycle effect) = in-use emission rate

Step 2: Tier 1 in-use emission rate * (percent reduction) = Tier 2 emission benefit (g/mi)

Step 3: (Tier 2 emission benefit (g/mi))*(discounted life time mileage)/(grams per ton conversion factor)= per vehicle Tier 2 emission benefit (tons)

Step 4: Per vehicle cost ($)/ per vehicle emission benefit (tons)= Cost effectiveness estimate ($/ton)

The attached spreadsheet provides the specific values used in carrying out the four steps discussed above.

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[7]The mileage applied to the deterioration factor is the average in-use mileage weighted by the fleet travel fraction to account for higher usage rate for new vehicles. The average for LDVs and LDT1s is 68,000 miles, while LDT2 is 81,000 miles, and LDT3 and LDT4 was 100,000 miles.

[8]For LDVs the lifetime mileage used is 132,000 miles discounted to 90,000 miles. the lifetime mileage used for LDTs is 154,000 discounted to 97,000 miles.

Tier 1 Emission rates and Tier 2 benefit calculations

NMHC

	CALIMFAC Tier 1 zero mile level	NMHC adj. factor	Off-cycle adj. factor	Deterioration Rate.	Avg. in-use mileage (1,000s)	In-use Tier 1 emission rate	Percent control	Tier 2 emission benefit
LDV(LDV&LDT1)	0.1569	0.868	1.070	0.0142	6.800	0.2353	77%	0.181
LDT (LDT2)	0.1440	0.868	1.070	0.0161	8.100	0.2547	77%	0.196
MDT(LDT3&LDT4)	0.1402	0.868	1.070	0.0160	10.000	0.2787	77%	0.215

NOx

	CALIMFAC Tier 1 zero mile level	NMHC adj. factor	Off-cycle adj. factor	Deterioration Rate.	Avg. in-use mileage	In-use Tier 1 emission rate	Percent control	Tier 2 emission benefit
LDV(LDV&LDT1)	0.3091	1.000	1.208	0.0188	6.800	0.5278	80%	0.422
LDT (LDT2)	0.3009	1.000	1.208	0.0205	8.100	0.5641	80%	0.451
MDT(LDT3&LDT4)	0.2976	1.000	1.208	0.0202	10.000	0.6035	80%	0.483

Light-duty VMT Fractions	Percent
LDV	51%
LDT1	10%
LDT2	23%
LDT3, LDT4	16%

		NMHC benefit	NOx benefit	NMHC+NOx benefit	Total Costs	NMHC $/ton	NOx $/ton	NMHC+NOx $/ton
LDV	0.51	0.181	0.422	0.603	136	**$3,306**	**$1,824**	**$2,269**
LDT	0.49	0.199	0.456	0.653	161	**$3,377**	**$1,824**	**$2,303**
LDT1		0.037	0.085	0.122				
LDT2		0.093	0.213	0.305				
LDT3 &LDT4		0.070	0.157	0.226				

Appendix D

CLASSIFICATION OF LDTs

In the Clean Air Act Amendments of 1990, Congress required that the smallest LDTs (LDT1s)[9] meet the same emission standards as LDVs. However, the emission standards for LDT2s, LDT3s and LDT4s remained less stringent than the LDV/LDT1 standards. The primary distinction between these LDT sub-categories and between the LDT and heavy-duty vehicle (HDV) categories is GVWR. Figure VI-1 describes the definition of the four LDT sub-classes and HDVs.

Because of this incentive, many LDT models have migrated to heavier categories with higher numerical emission standards. For example, 57% of all LDTs certified in 1987 would have fallen into the lightest current LDT sub-category (LDT1). This would have included the Chrysler minivans, the Jeep Cherokee and Wrangler and most Bronco II and Blazer models. By 1996, only 16% of all LDTs certified were LDT1s. Essentially all minivans are now LDT2s, as are all compact sport utility vehicles.

Also, a number of previous LDTs now have GVWRs which exceed 8500 pounds, which moves them into the HDV category. Examples are many Ford F250 and all F350 pick-ups, the GMC 3500 full-sized van and the GMC Suburban 2500.

Table VI-1 shows the current 100,000-mile, California LEV standards for LDVs and LDTs (vehicle categoreis as defined by EPA). Also shown are the fleet-wide average standards using the in-use VMT fractions developed in Chapter III. As can be seen, the fleet-average NMHC and NOx standards are nearly 50% higher than the LEV standards for LEVs.

Table VI-1. LEV Emission Standards (g/mi @ 100,000 miles)

	NMHC[10]	NOx	NMHC+NOx
LDV	0.09	0.3	0.39
LDT1	0.09	0.3	0.39
LDT2	0.13	0.5	0.63
LDT3 (MDV2)	0.23	0.6	0.83
LDT4 (MDV3)	0.28	0.9	1.18
Weighted Average	0.138	0.437	0.575

[9] LDTs with a curb weight of 3450 pounds or less and a gross vehicle weight rating (GVWR) of less than 8500 pounds.

[10] The California standards are actually in terms of non-methane organic gases, or NMOG, which is nearly equivalent to NMHC.

Table VI-2 compares the emission reduction potential of equating the LDV and LDT standards at the LDV LEV level with that resulting from a 50% reduction in all of the current LEV standards (e.g., 0.045 and 0.10 g/mi NMHC and NOx for LDVs, respectively). As can be seen, the two strategies yield almost equivalent reductions in in-use emissions. This highlights the need to address the relationship between the LDV and LDT standards in the process of considering tighter emission standards for both vehicle classes.

Table VI-2. Emission Reductions Associated with Various LDV/LDT Control Strategies (g/mi)

	NMHC	NOx	NMHC+NOx
Baseline			
LDTs Meet LDV Standards	0.048	0.137	0.185
50% Reduction from LEV Standards	0.045	0.150	0.195